



PUBLISHED FOR SISSA BY SPRINGER

RECEIVED: October 30, 2012

ACCEPTED: December 10, 2012

PUBLISHED: January 10, 2013

Search for supersymmetry in final states with missing transverse energy and 0, 1, 2, or ≥ 3 b-quark jets in 7 TeV pp collisions using the variable α_T



The CMS collaboration

E-mail: cms-publication-committee-chair@cern.ch

ABSTRACT: A search for supersymmetry in final states with jets and missing transverse energy is performed in pp collisions at a centre-of-mass energy of $\sqrt{s} = 7$ TeV. The data sample corresponds to an integrated luminosity of 4.98 fb^{-1} collected by the CMS experiment at the LHC. In this search, a dimensionless kinematic variable, α_T , is used as the main discriminator between events with genuine and misreconstructed missing transverse energy. The search is performed in a signal region that is binned in the scalar sum of the transverse energy of jets and the number of jets identified as originating from a bottom quark. No excess of events over the standard model expectation is found. Exclusion limits are set in the parameter space of the constrained minimal supersymmetric extension of the standard model, and also in simplified models, with a special emphasis on compressed spectra and third-generation scenarios.

KEYWORDS: Hadron-Hadron Scattering

ARXIV EPRINT: [1210.8115](https://arxiv.org/abs/1210.8115)

Contents

1	Introduction	1
2	The CMS apparatus	2
3	Object definitions and event reconstruction	3
4	Selecting events with missing transverse energy	4
5	Background estimation from data	5
5.1	Definition of data control samples	6
5.2	Method and systematic studies	7
6	Results	9
7	Interpretation of the results	11
7.1	Interpretation in the CMSSM	12
7.2	Interpretation with simplified models	15
8	Summary	18
	The CMS collaboration	23

1 Introduction

Supersymmetry (SUSY) is generally regarded as one of the likely extensions to the standard model (SM) of particle physics [1–8]. It is based on the unique extension of the space-time symmetry group underpinning the SM, introducing a relationship between fermions and bosons. A low-energy realisation of SUSY, e.g. at the TeV scale, is motivated by the cancellation of the quadratically divergent loop corrections to the Higgs boson mass in the SM [7, 8]. These corrections are proportional to the masses of the particles that couple to the Higgs boson. The most relevant terms come from the interplay between the masses of the third generation (top and bottom) squarks, and the largest Yukawa coupling (of the top quark).

In order to avoid large cancellations in these loop corrections, the difference in masses between the top quark and the third generation squarks must not be too large [9]. While the majority of SUSY particles might not be accessible at the present energy and luminosity delivered by the Large Hadron Collider (LHC), the recent discovery of a low-mass Higgs boson candidate [10, 11] motivates models in which top and bottom squarks appear at the TeV scale. Furthermore, if the multiplicative quantum number R-parity [12] is conserved, SUSY particles will be produced in pairs and decay to SM particles and the lightest SUSY

particle (LSP), which is generally assumed to be weakly interacting and massive. This would result in a final state that is rich in jets, especially those originating from bottom quarks, and contains a significant amount of missing transverse energy, \cancel{E}_T .

This paper summarises a search that is designed to be sensitive to missing transverse energy signatures in events with two or more energetic jets that are categorised according to the number of reconstructed jets originating from bottom quarks (b-quark jets) per event. With respect to previous searches [13, 14], this refinement provides improved sensitivity to third generation squark signatures. However, the same inclusive search strategy is deployed, thus maintaining the ability to identify a wide variety of SUSY event topologies arising from the pair production and decay of massive coloured sparticles.

The ATLAS and Compact Muon Solenoid (CMS) experiments have performed various searches [13–21] for the production of massive coloured particles and their subsequent decay to a final state of jets and missing transverse energy. These searches were performed with a dataset of pp collisions at $\sqrt{s} = 7$ TeV, and no significant deviations from SM expectations were observed. The majority of these searches have been interpreted in the context of a specific model of SUSY breaking, the constrained minimal supersymmetric extension of the standard model (CMSSM) [22–24]. The simplifying assumption of this model is universality at an energy scale of $\mathcal{O}(10^{16})$ GeV which makes the CMSSM a useful framework to study SUSY phenomenology at colliders, and to serve as a benchmark for the performance of experimental searches.

However, the universality conditions of the CMSSM result in significant restrictions on the possible SUSY particle mass spectra and thus kinematic signatures. This limits the interpretation of the results in scenarios such as the direct production of third-generation squarks and compressed spectra, where the mass difference between the primary produced sparticle (e.g., a squark or a gluino) and the LSP is small. Therefore, in order to complement the interpretation within the CMSSM, simplified models [25–27] are also used to interpret the search results. These models are characterised using a limited set of SUSY particles (production and decay) and enable comprehensive studies of individual SUSY event topologies. The simplified model studies can be performed without limitations on fundamental properties such as decay modes, production cross sections, and sparticle masses. A special emphasis is placed on interpretation within models involving compressed spectra or third generation squarks.

2 The CMS apparatus

The central feature of the CMS detector is a superconducting solenoid, which provides an axial magnetic field of 3.8 T. The bore of the solenoid is instrumented with several particle detection systems. Silicon pixel and strip tracking systems measure charged particle trajectories with full azimuthal (ϕ) coverage and a pseudorapidity acceptance of $|\eta| < 2.5$, where $\eta = -\ln[\tan(\theta/2)]$ and θ is the polar angle with respect to the counterclockwise beam direction. The resolutions on the transverse momentum (p_T) and impact parameter of a charged particle with $p_T < 40$ GeV are typically 1% and $15 \mu\text{m}$, respectively. A lead-tungstate crystal electromagnetic calorimeter (ECAL) and a brass/scintillator hadron

calorimeter surround the tracking volume. The region outside the solenoid is covered by an iron/quartz-fiber hadron calorimeter. The ECAL covers $|\eta| < 3.0$ and provides an energy resolution of better than 0.5% for unconverted photons with transverse energies above 100 GeV. The hadron calorimeters cover $|\eta| < 5.0$ with a resolution in jet energy, E (GeV), of about $100\%/\sqrt{E}$ for the region $|\eta| < 3.0$. Muons are identified in gas-ionization detectors, covering $|\eta| < 2.4$, embedded in the steel return yoke. The CMS detector is nearly hermetic, which allows momentum-balance measurements in the plane transverse to the beam axis. A two-tier trigger system is designed to select the most interesting pp collision events for use in physics analysis. A detailed description of the CMS detector can be found elsewhere [28].

3 Object definitions and event reconstruction

The event reconstruction and selection criteria follow the procedure described in refs. [13, 14]. Jets are reconstructed from energy deposits in the calorimeters, clustered by the anti- k_T algorithm [29] with a distance parameter of 0.5. The raw jet energies measured by the calorimeter systems are corrected to establish a uniform relative response in η and a calibrated absolute response in transverse momentum with an associated uncertainty between 2% and 4%, depending on the jet η and p_T [30]. Jets considered in the analysis are required to have transverse energy $E_T > 50$ GeV and the two highest- E_T jets must each satisfy $E_T > 100$ GeV. These two E_T requirements change under special circumstances described in section 4. The highest- E_T jet is additionally required to be within the central tracker acceptance ($|\eta| < 2.5$). Events are vetoed if any additional jet satisfies both $E_T > 50$ GeV and $|\eta| > 3$, or rare, spurious signals are identified in the calorimeters [31]. To suppress SM processes with genuine \cancel{E}_T from neutrinos in the final state, an event is vetoed if it contains an isolated electron [32] or muon [33] with $p_T > 10$ GeV. Further, events with an isolated photon [34] with $p_T > 25$ GeV are also vetoed.

The presence of a b-quark jet is identified through a vertex that is displaced with respect to the primary interaction, using an algorithm that attempts to reconstruct a secondary vertex using tracks from charged particles associated to each jet. Using a likelihood ratio technique, the combined secondary vertex algorithm [35] incorporates several variables related to the vertex, such as decay length significance, mass, and track multiplicity, to build a discriminator that distinguishes between jets originating from bottom quarks and those from other sources. These include jets from charm quarks (c-quark jets) and light-flavour quarks. The algorithm also provides a value for this discriminator based on single-track properties, when no secondary vertices have been reconstructed. Discriminator values above a certain threshold are used to tag jets as originating from b quarks. This threshold is chosen such that the mistagging rate, the probability to tag a jet originating from a light-flavour quark, is approximately 1% for jets with transverse momenta of 80 GeV [35, 36]. The same threshold results in a b-tagging efficiency, the probability to correctly tag a jet as originating from a bottom quark, in the range 60–70% [35, 36].

The following two variables characterise the visible energy and missing momentum in the transverse plane: the scalar sum of the transverse energy E_T of jets, defined as $H_T = \sum_{i=1}^{N_{\text{jet}}} E_T^{j_i}$, and the magnitude of the vector sum of the transverse momenta $p_T^{\vec{}}$ of

jets, defined as $\#_T = |\sum_{i=1}^{N_{\text{jet}}} \vec{p}_T^{j_i}|$, where N_{jet} is the number of jets above the E_T threshold. Significant hadronic activity in the event is ensured by requiring $H_T > 275$ GeV. Following these selections, the background from multijet production, a manifestation of quantum chromodynamics (QCD), is still several orders of magnitude larger than the typical yields expected from a SUSY signal.

4 Selecting events with missing transverse energy

The α_T kinematic variable [13, 37] is used to efficiently reject multijet events without significant \cancel{E}_T , including those with transverse energy mismeasurements, while retaining a large sensitivity to new physics with genuine \cancel{E}_T signatures. For dijet events, the α_T variable is defined as:

$$\alpha_T = \frac{E_T^{j_2}}{M_T}, \quad M_T = \sqrt{\left(\sum_{i=1}^2 E_T^{j_i}\right)^2 - \left(\sum_{i=1}^2 p_x^{j_i}\right)^2 - \left(\sum_{i=1}^2 p_y^{j_i}\right)^2}. \quad (4.1)$$

where $E_T^{j_2}$ is the transverse energy of the less energetic jet, and M_T is the transverse mass of the dijet system. For a perfectly measured dijet event with $E_T^{j_1} = E_T^{j_2}$ and jets back-to-back in ϕ , and in the limit in which each jet's momentum is large compared with its mass, the value of α_T is 0.5. In the case of an imbalance in the measured transverse energies of back-to-back jets, α_T is smaller than 0.5. Values significantly greater than 0.5 are observed when the two jets are not back-to-back, recoiling against genuine \cancel{E}_T .

For events with three or more jets, an equivalent dijet system is formed by combining the jets in the event into two pseudo-jets. The E_T of each of the two pseudo-jets is calculated as the scalar sum of the measured E_T of the contributing jets. The combination chosen is the one that minimises the E_T difference (ΔH_T) between the two pseudo-jets. This simple clustering criterion provides the best separation between multijet events and events with genuine \cancel{E}_T . Thus, in the case of events with at least three jets, the α_T variable can be defined as:

$$\alpha_T = \frac{1}{2} \cdot \frac{H_T - \Delta H_T}{\sqrt{H_T^2 - \cancel{E}_T^2}} = \frac{1}{2} \cdot \frac{1 - (\Delta H_T/H_T)}{\sqrt{1 - (\cancel{E}_T/H_T)^2}} \quad (4.2)$$

Events with extremely rare but large stochastic fluctuations in the calorimetric measurements of jet energies can lead to values of α_T slightly above 0.5. Such events are rejected by requiring $\alpha_T > 0.55$. A similar behaviour is observed in events with reconstruction failures, severe energy losses due to detector inefficiencies, or jets below the E_T threshold that result in significant \cancel{E}_T relative to the value of \cancel{E}_T (as measured by the calorimeter systems, which is not affected by jet E_T thresholds). These classes of events are rejected by applying dedicated vetoes, described further in ref. [14]. The leakage above 0.5 becomes smaller with increasing H_T due to the increase in average jet energy and thus an improvement in jet energy resolution. Further, the relative impact of jets falling below the E_T threshold is reduced as the energy scale of the event (i.e. H_T) increases.

The signal region is defined by $H_T > 275$ GeV and $\alpha_T > 0.55$, which is divided into eight bins in H_T : two bins of width 50 GeV in the range $275 < H_T < 375$ GeV, five bins of width 100 GeV in the range $375 < H_T < 875$ GeV, and a final open bin, $H_T > 875$ GeV. As in ref. [14], the jet E_T threshold is scaled for the two lowest H_T bins leading to thresholds of 37 GeV and 43 GeV. The two highest- E_T jet thresholds are scaled to 73 GeV and 87 GeV. This approach maintains SM background admixtures and event kinematics similar to those observed for the higher H_T bins. Events are further categorised according to whether they contain exactly zero, one, two, or at least three reconstructed b-quark jets.

Events in the signal region are recorded with a dedicated trigger condition that must satisfy simultaneously the requirements $H_T > 250$ GeV and $\alpha_T > 0.53$, with the latter threshold increasing to 0.60 towards the end of 2011 due to higher instantaneous luminosities. The efficiency with which events that would satisfy the signal region selection criteria also satisfy the trigger conditions is measured in data to be $(82.8 \pm 1.1)\%$, $(95.9 \pm 0.9)\%$, and $(> 98.5 \pm 0.9)\%$ for the regions $275 < H_T < 325$ GeV, $325 < H_T < 375$ GeV, and $H_T > 375$ GeV, respectively.

A disjoint hadronic control sample consisting predominantly of multijet events is defined by inverting the α_T requirement for a given H_T region, which is used primarily in the estimation of any residual background from multijet events. These events are recorded by a set of triggers with thresholds only in H_T .

5 Background estimation from data

Once all the signal region selection requirements have been imposed, the contribution from multijet events is expected to be negligible. The remaining significant backgrounds in the signal region stem from SM processes with genuine \cancel{E}_T in the final state. In the case of events where no b-quark jets are identified, the largest backgrounds with genuine \cancel{E}_T arise from the production of W and Z bosons in association with jets. The weak decay $Z \rightarrow \nu\bar{\nu}$ is the only significant contribution from Z + jets events. For W + jets events, the two dominant sources are leptonic W decays in which the lepton is not reconstructed or fails the isolation or acceptance requirements, and the weak decay $W \rightarrow \tau\nu$ where the τ decays hadronically and is identified as a jet. Contributions from SM processes such as single-top, Drell-Yan, and diboson production are also expected. For events with one or more reconstructed b-quark jets, $t\bar{t}$ production followed by semi-leptonic weak decays becomes the most important single background source. For events with only one reconstructed b-quark jet, the contribution of both W + jets and Z + jets backgrounds are of a similar size to the $t\bar{t}$ background. For events with two reconstructed b-quark jets, $t\bar{t}$ production dominates, while events with three or more reconstructed b-quark jets originate almost exclusively from $t\bar{t}$ events, in which at least one jet is misidentified as originating from a bottom quark.

In order to estimate the contributions from each of these backgrounds, three data control samples are used, which are binned in the same way as the signal region. The irreducible background of $Z \rightarrow \nu\bar{\nu}$ + jets events in the signal region is estimated from two independent data samples of $Z \rightarrow \mu\mu$ + jets and γ + jets events, both of which share the kinematic properties of $Z \rightarrow \nu\bar{\nu}$ + jets but have different acceptances. The $Z \rightarrow \mu\mu$ +

jets events have identical kinematic properties to the $Z \rightarrow \nu\bar{\nu} + \text{jets}$ background when the two muons are ignored, but a smaller branching fraction, while the $\gamma + \text{jets}$ events have similar kinematic properties when the photon is ignored [13, 38], but a larger production cross section. A $\mu + \text{jets}$ data sample provides an estimate for all other SM backgrounds, which is dominated by $t\bar{t}$ and W production leading to W + jets final states.

The event selection criteria for the control samples are defined to ensure that any potential contamination from multijet events is negligible. Further, the same selection criteria also strongly suppress contributions from a wide variety of SUSY models, including those considered in this analysis. Any potential signal contamination in the data control samples is accounted for in the fitting procedure described in section 6.

5.1 Definition of data control samples

The $\mu + \text{jets}$ sample is recorded using two different trigger strategies, to account for evolving trigger conditions during the 2011 run. The hadronic trigger condition, combining H_T and α_T , is used for the region $275 < H_T < 375 \text{ GeV}$. Here, the event selection, following closely the prescription described in ref. [39], requires exactly one isolated muon that satisfies stringent quality criteria, with $p_T > 10 \text{ GeV}$ and $|\eta| < 2.1$. In order for the trigger to be maximally efficient, the requirement $\alpha_T > 0.55$ is also imposed. For the region $H_T > 375 \text{ GeV}$, the trigger condition requires both a muon above a p_T threshold as high as 40 GeV and $H_T > 300 \text{ GeV}$. The muon must satisfy $p_T > 45 \text{ GeV}$ in order for the trigger to be maximally efficient, at $(91.3 \pm 0.1)\%$. The requirement $\alpha_T > 0.55$ is again imposed when zero b-quark jets are reconstructed per event. For events in which at least one b-quark jet is reconstructed, no α_T requirement is used. This approach increases the statistical precision of predictions derived from event samples containing b-quark jets, while the impact of relaxing the α_T requirement is tested with a dedicated set of closure tests described in section 5.2.

In addition to the requirements described above, further selection criteria are applied. The transverse mass of the muon and \cancel{E}_T system must be larger than 30 GeV to ensure a sample rich in W bosons. The muon is required to be separated from the closest jet in the event by $\Delta\eta$ and $\Delta\phi$ such that the distance $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} > 0.5$. To ensure that this sample is disjoint from the $\mu\mu + \text{jets}$ sample, the event is rejected if a second muon candidate is identified that does not satisfy all quality criteria or is non-isolated or is outside the acceptance, and the two muon candidates have an invariant mass that is within a window of $\pm 25 \text{ GeV}$ around the mass of the Z boson.

The $\mu\mu + \text{jets}$ sample follows the same trigger strategy and muon identification criteria as the $\mu + \text{jets}$ sample. The event selection requires exactly two oppositely charged, isolated muons satisfying stringent quality criteria, and an invariant mass within a window of $\pm 25 \text{ GeV}$ around the mass of the Z boson. Each muon is required to be separated from the nearest jet in the event by the distance $\Delta R > 0.5$. The same α_T requirements are used as for the $\mu + \text{jets}$ sample.

The $\gamma + \text{jets}$ sample is selected using a dedicated photon trigger condition requiring a localised energy deposit in the ECAL with $E_T > 135 \text{ GeV}$ that satisfies loose photon identification and isolation criteria [34]. The event selection requires $H_T > 375 \text{ GeV}$, $\alpha_T > 0.55$, and a single photon to be reconstructed with $E_T > 150 \text{ GeV}$, $|\eta| < 1.45$,

satisfying tight isolation criteria, and with a minimum distance to any jet of $\Delta R > 1.0$. For these selection criteria, the photon trigger condition is found to be fully efficient.

5.2 Method and systematic studies

The method used to estimate the SM background contributions in the signal region relies on the use of transfer factors, which are functions of H_T and the number of b-quark jets per event, n_b , and are computed separately for each data control sample. These transfer factors are determined from simulation samples generated with MADGRAPH v4.22 [40] interfaced to PYTHIA 6.4 tune Z2 [41], and the GEANT 4-based [42] CMS detector simulation. Each factor is defined as the ratio of yields from simulation in a given bin of the signal region, $N_{MC}^{\text{signal}}(H_T, n_b)$ and the corresponding bin of one control sample, $N_{MC}^{\text{control}}(H_T, n_b)$. The factors are used to translate the observed yield measured in a control sample bin, $N_{\text{obs}}^{\text{control}}(H_T, n_b)$ into an expectation for one or more SM background processes in the corresponding bin of the signal region, $N_{\text{pred}}^{\text{signal}}(H_T, n_b)$:

$$N_{\text{pred}}^{\text{signal}}(H_T, n_b) = N_{\text{obs}}^{\text{control}}(H_T, n_b) \times \frac{N_{MC}^{\text{signal}}(H_T, n_b)}{N_{MC}^{\text{control}}(H_T, n_b)}. \quad (5.1)$$

In order to maximise sensitivity to potential new physics signatures in final states with multiple b-quark jets, a method that improves the statistical power of the predictions from simulation, particularly for $n_b \geq 2$, is employed. The distribution of n_b is estimated from generator-level information contained in the simulation, namely the number of reconstruction-level jets matched to underlying b quarks, n_b^{gen} , and light quarks, n_q^{gen} , per event. All relevant combinations of n_b^{gen} and n_q^{gen} are considered, and event counts are recorded in bins of H_T for each combination $N(n_b^{\text{gen}}, n_q^{\text{gen}}, H_T)$. The b-tagging efficiency, ϵ , and a flavour-averaged mistagging rate, m , are also determined from simulation for each H_T bin, with both quantities averaged over jet p_T and η . Corrections are applied on a jet-by-jet basis to both ϵ and m in order to match the corresponding measurements with data [35, 36]. This information is sufficient to predict n_b and thus also determine the yield from simulation for a given bin, $N(H_T, n_b)$:

$$N(H_T, n_b) = \sum_{n_b^{\text{gen}} + n_q^{\text{gen}} = N_{\text{jet}}} \sum_{n_b^{\text{tag}} + n_q^{\text{tag}} = n_b} N(n_b^{\text{gen}}, n_q^{\text{gen}}, H_T) \times P(n_b^{\text{tag}}; n_b^{\text{gen}}, \epsilon) \times P(n_q^{\text{tag}}; n_q^{\text{gen}}, m) \quad (5.2)$$

where n_b^{tag} and n_q^{tag} are the number of times a reconstruction-level b-quark jet originates from an underlying b-quark and light-quark respectively, and $P(n_b^{\text{tag}}; n_b^{\text{gen}}, \epsilon)$ and $P(n_q^{\text{tag}}; n_q^{\text{gen}}, m)$ are the binomial probabilities for this to happen. The predicted yields are found to be in good agreement with the yields obtained directly from the simulation in those bins with significant population.

The method exploits the ability to determine precisely $N(n_b^{\text{gen}}, n_q^{\text{gen}}, H_T)$, ϵ , and m independently of n_b , which means that event yields for a given b-quark jet multiplicity can be predicted with a higher statistical precision than obtained directly from simulation. A precise determination of m is particularly important for events with $n_b \geq 3$, which occurs

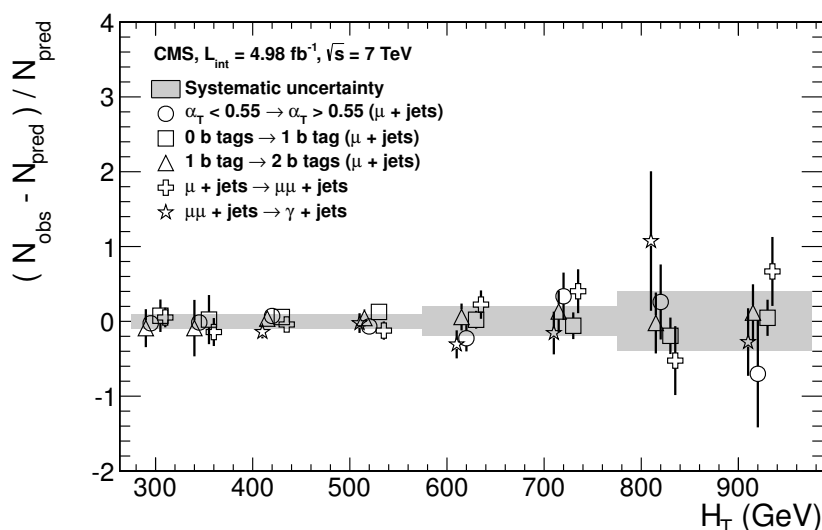


Figure 1. A set of five closure tests, described in the text, that use the three data control samples to probe key ingredients of the simulation modelling of the SM backgrounds, as a function of H_T . Error bars represent statistical uncertainties only. The shaded bands represent the H_T -dependent systematic uncertainties assigned to the transfer factors.

in the SM because of the presence of mistagged jets in the event. In this case, the largest background is $t\bar{t}$, with two correctly tagged b-quark jets and an additional mistagged jet.

The magnitudes of the transfer factors are dependent on the control sample and independent of the b-quark jet multiplicity, within statistical uncertainties. For the $\gamma + \text{jets}$ sample, the factors are also independent of H_T with values of approximately 0.4. For the $\mu + \text{jets}$ and $\mu\mu + \text{jets}$ control samples, for which the α_T requirement is dropped from the selection criteria in the region $H_T > 375 \text{ GeV}$, the factors decrease smoothly with increasing H_T and are in the ranges 0.2 to 0.05 and 2 to 0.33, respectively. This variation arises from $W + \text{jets}$ and $Z + \text{jets}$ events in the signal region, for which the efficiency of the $\alpha_T > 0.55$ requirement is dependent on H_T .

A systematic uncertainty is assigned to each transfer factor to account for theoretical uncertainties [38] and also for limitations in the simulation modelling of event kinematics [13]. The magnitudes of the uncertainties are determined from a representative set of closure tests in data, in which yields from one of the three independent control samples, along with the corresponding transfer factors obtained from simulation, are used to predict the yields in another control sample, following the same prescription defined in eq. (5.1). Hence, the closure tests provide a consistency check between the predicted and observed yields in the data control samples, from which the validity of the method and the transfer factors can be established.

A set of five closure tests use the three data control samples to probe key ingredients of the simulation modelling of the SM backgrounds with genuine \cancel{E}_T as a function of H_T , as shown in figure 1. The first three closure tests are carried out within the $\mu + \text{jets}$ sample,

and probe the modelling of the α_T distribution in genuine \cancel{E}_T events (circles), the relative contributions of $W + \text{jets}$ and $t\bar{t}$ events (squares), and the modelling of the reconstruction of b-quark jets (triangles), respectively. The fourth test (crosses), connecting the $\mu + \text{jets}$ and $\mu\mu + \text{jets}$ control samples, addresses the modelling of the relative contributions of $Z + \text{jets}$ to the sum of both $W + \text{jets}$ and $t\bar{t}$ events, while the fifth test (stars) deals with the consistency between the $Z \rightarrow \mu\mu + \text{jets}$ and $\gamma + \text{jets}$ samples. All individual closure tests demonstrate, within the statistical precision of each test, that there are no significant biases inherent in the transfer factors obtained from simulation. The level of closure achieved in these tests is used to estimate the systematic uncertainties that are assigned to the transfer factors, which are determined for three regions $275 < H_T < 575 \text{ GeV}$, $575 < H_T < 775 \text{ GeV}$, and $H_T > 775 \text{ GeV}$ to be 10%, 20%, and 40%, respectively.

A further dedicated study to account for potential systematic effects arising from the modelling of the reconstruction of b-quark jets in the simulation has been performed. After correcting the efficiency and mistagging rates of b-quark jets in simulation for residual differences as measured in data, the corresponding uncertainties on these corrections are propagated to the transfer factors and found to be at the sub-percent level. In addition, several robustness tests are performed, including treating c-quark jets as b-quark jets in the yield estimates throughout, as well as ignoring the contribution from hadronic τ -lepton decays. These tests also demonstrate sub-percent effects on the transfer factors, highlighting the insensitivity to potential mismodelling in simulation. Hence, the H_T -dependent systematic uncertainties of 10%, 20%, and 40% are used for all b-quark jet multiplicities.

6 Results

A likelihood model of the observations in all four data samples is used to obtain a consistent prediction of the SM background, and to test for the presence of a variety of signal models. It is written as

$$L_{\text{total}} = \prod_{n_b=0}^2 \left(L_{\text{hadronic}}^{n_b} \times L_{\mu+\text{jets}}^{n_b} \times L_{\mu\mu+\text{jets}}^{n_b} \times L_{\gamma+\text{jets}}^{n_b} \right) \times L_{\text{hadronic}}^{\geq 3} \times L_{\mu+\text{jets}}^{\geq 3}, \quad (6.1)$$

where $L_{\text{hadronic}}^{n_b}$ describes the yields in the eight H_T bins of the signal region when exactly n_b reconstructed b-quark jets are required. In each bin of H_T , the observation is modelled as Poisson-distributed about the sum of a SM expectation and a potential signal contribution. The components of this SM expectation are related to the expected yields in the control samples via transfer factors derived from simulation, as described in section 5.2. Signal contributions in each of the four data samples are considered, though the only significant contribution occurs in the signal region and not the control samples. The systematic uncertainties associated with the transfer factors are accounted for with nuisance parameters, the measurements of which are treated as normally-distributed. Since for $n_b \geq 3$ the dominant SM background arises from top events, only the $\mu + \text{jets}$ control sample is used in the likelihood to determine the total contribution from all (non-multijet) SM backgrounds in the signal region.

$\backslash H_T$ [GeV]	275–325	325–375	375–475	475–575	575–675	675–775	775–875	>875
# b-quark jets\								
0 (SM)	2933^{+56}_{-52}	1139^{+17}_{-40}	783^{+17}_{-27}	261^{+14}_{-8}	$81.5^{+6.5}_{-6.5}$	$34.2^{+4.0}_{-3.8}$	$10.4^{+2.8}_{-1.8}$	$5.3^{+1.7}_{-1.1}$
0 (Data)	2919	1166	769	255	91	31	10	4
1 (SM)	630^{+26}_{-25}	271^{+10}_{-16}	202^{+10}_{-6}	$78.0^{+6.9}_{-1.9}$	$24.2^{+2.9}_{-2.0}$	$10.6^{+1.7}_{-1.3}$	$2.9^{+0.9}_{-0.5}$	$2.2^{+0.7}_{-0.4}$
1 (Data)	614	294	214	71	20	6	4	0
2 (SM)	162^{+13}_{-12}	$61.8^{+4.8}_{-6.3}$	$58.8^{+4.8}_{-2.6}$	$28.0^{+3.5}_{-1.1}$	$9.0^{+1.4}_{-1.0}$	$7.1^{+1.4}_{-1.0}$	$0.6^{+0.3}_{-0.2}$	$0.9^{+0.4}_{-0.2}$
2 (Data)	160	68	52	19	11	7	0	2
≥ 3 (SM)	$10.5^{+3.5}_{-2.2}$	$7.1^{+2.2}_{-1.8}$	$5.8^{+1.4}_{-0.9}$	$3.1^{+1.0}_{-0.7}$	$1.7^{+0.5}_{-0.4}$	$0.7^{+0.5}_{-0.4}$	$0.1^{+0.1}_{-0.1}$	$0.2^{+0.1}_{-0.1}$
≥ 3 (Data)	10	8	8	1	0	0	0	0

Table 1. Comparison of the observed yields in the different H_T and b-quark jet multiplicity bins for the signal region with the SM expectations and combined statistical and systematic uncertainties given by the simultaneous fit.

In addition, any potential contribution from multijet background in the signal region is accounted for by using the ratio of events which result in a value of α_T above and below some threshold value for a given H_T bin. The dependence of this ratio, R_{α_T} , on H_T is modelled as a falling exponential function: $A_{n_b} e^{-k H_T}$ [14]. A common parameter k is used for all four categories of b-quark jet multiplicity, and is constrained via measurements in a multijet-enriched data side-band satisfying the criteria $H_T < 575$ GeV and $0.52 < \alpha_T < 0.55$. A further side-band, defined by inverting the $\cancel{H}_T/\cancel{E}_T$ requirement of ref. [14], is used to confirm that this method provides an unbiased estimate of k and to determine a systematic uncertainty.

In order to test the compatibility of the observed yields with the expectations from SM processes only, signal contributions are fixed to zero and the likelihood function is maximised over all parameters. The maximum likelihood values of the multijet normalisation parameters A_{n_b} are found to be compatible with zero, within uncertainties, confirming the hypothesis that the multijet background is negligible after the final selection. Further, the SM expected yields obtained from an alternate fit, in which these normalisation parameters are fixed to zero, agree well with those obtained from the nominal fit.

The signal region data yields, as well as the SM expectations obtained from the simultaneous fit across all samples, are shown in table 1. A comparison of the observed yields and the SM expectations in bins of H_T for events with exactly zero, one, two, and at least three reconstructed b-quark jets are shown in figures 2, 3, 4, and 5, respectively, for the signal region and the three control samples. In all four categories of b-quark jet multiplicity, the samples are well described by the SM hypothesis. In particular, no significant excess above the SM expectation is observed in the signal region.

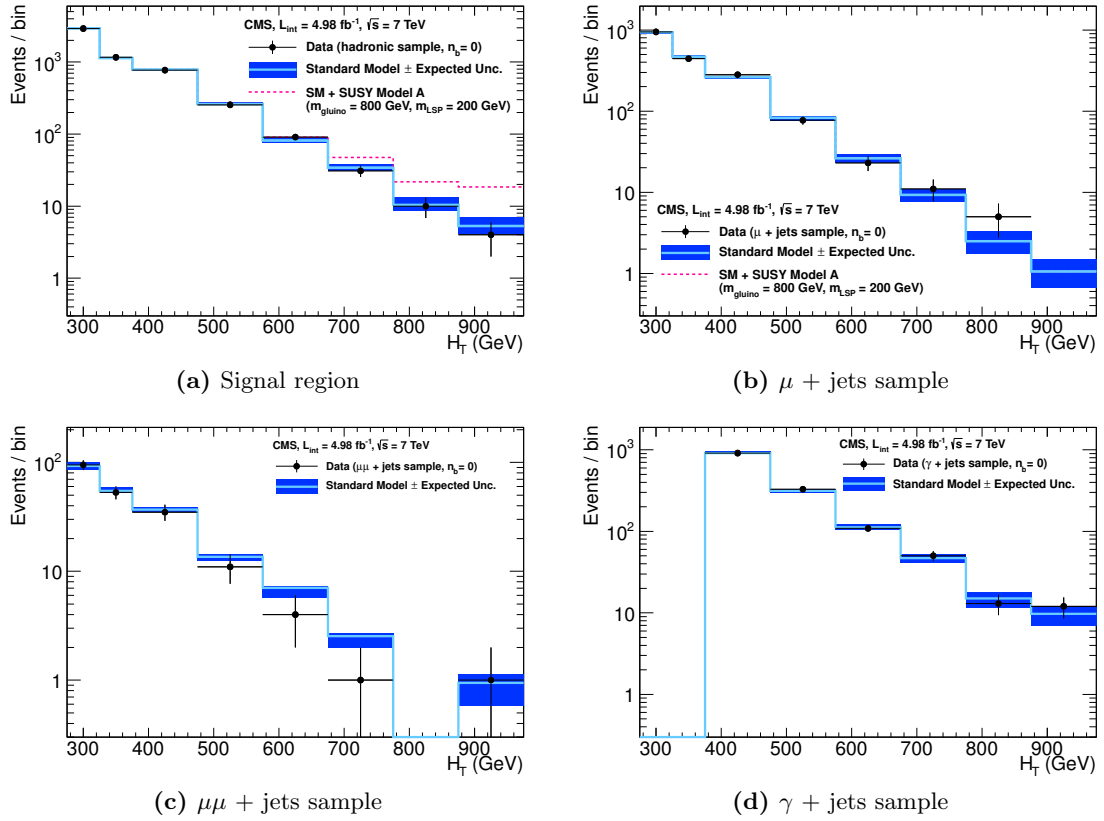


Figure 2. Comparison of the observed yields and SM expectations given by the simultaneous fit in bins of H_T for the (a) signal region, (b) $\mu + \text{jets}$, (c) $\mu\mu + \text{jets}$, and (d) $\gamma + \text{jets}$ samples when requiring exactly zero reconstructed b-quark jets. The observed event yields in data (black dots) and the expectations and their uncertainties, as determined by the simultaneous fit, for all SM processes (light blue solid line with dark blue bands) are shown. For illustrative purposes only, the signal expectation (magenta dashed line) in the signal region for the simplified model A (defined in section 7.2) with $m_{\tilde{g}} = 800 \text{ GeV}$ and $m_{LSP} = 200 \text{ GeV}$ is superimposed on the SM background expectation.

7 Interpretation of the results

Limits are set in the parameter space of the CMSSM and in a set of simplified models that characterise both third-generation squark production and compressed SUSY spectra scenarios. The CL_s method [43, 44] is used to compute the limits, with the one-sided profile likelihood ratio as the test statistic [45]. The sampling distributions for the test statistic are built by generating pseudo-data from the likelihood function, using the respective maximum-likelihood values of the nuisance parameters under the background-only and signal-plus-background hypotheses.

Events samples for the CMSSM and simplified models are generated at leading order with PYTHIA 6.4 [41]. Inclusive, process-dependent, next-to-leading order calculations with next-to-leading logarithmic corrections [46–50] (NLO+NLL) of SUSY production cross

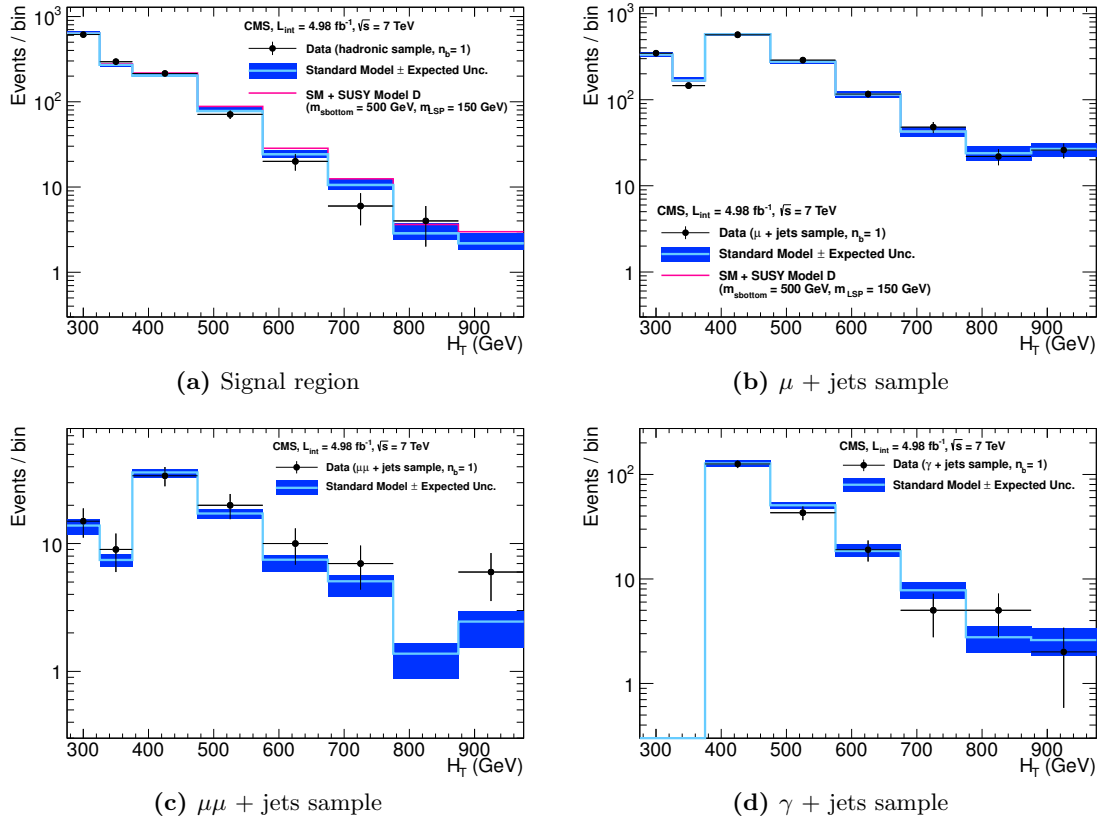


Figure 3. Comparison of the observed yields and SM expectations given by the simultaneous fit in bins of H_T for the (a) signal region, (b) $\mu + \text{jets}$, (c) $\mu\mu + \text{jets}$, and (d) $\gamma + \text{jets}$ samples. Same as figure 2, except requiring exactly one reconstructed b-quark jet. The observed event yields in data (black dots) and the expectations and their uncertainties, as determined by the simultaneous fit, for all SM processes (light blue solid line with dark blue bands) are shown. For illustrative purposes only, the signal expectation (magenta solid line) in the signal region for the simplified model D (defined in section 7.2) with $m_{\tilde{g}} = 500$ GeV and $m_{\text{LSP}} = 150$ GeV is superimposed on the SM background expectation.

sections are obtained with the program PROSPINO [51] and CTEQ6M [52] parton distribution functions. The simulated signal events include multiple interactions per LHC bunch crossing (pileup) with the distribution of reconstructed vertices that match the one observed in data.

7.1 Interpretation in the CMSSM

The CMSSM is described by the following five parameters: the universal scalar and gaugino mass parameters, m_0 and $m_{1/2}$; the universal trilinear soft SUSY-breaking parameter, A_0 ; the ratio of the vacuum expectation values of the two Higgs doublets, $\tan \beta$; and the sign of the Higgs mixing parameter, μ . At each point in the parameter space of the CMSSM, the SUSY particle spectrum is calculated with SOFTSUSY [53]. Experimental uncertainties on the SM background prediction (10–40%), the luminosity measurement (2.2%) [54], and

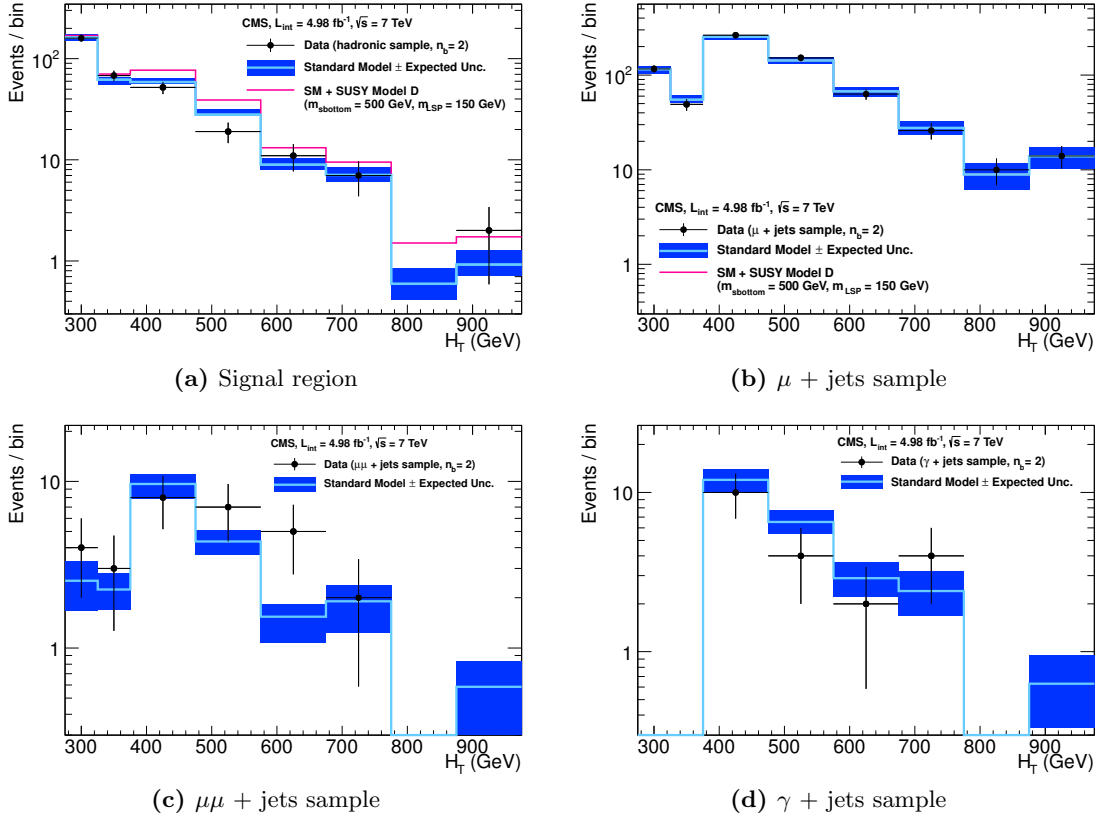


Figure 4. Comparison of the observed yields and SM expectations given by the simultaneous fit in bins of H_T for the (a) signal region, (b) $\mu + \text{jets}$, (c) $\mu\mu + \text{jets}$, and (d) $\gamma + \text{jets}$ samples. Same as figure 2, except requiring exactly two reconstructed b-quark jets. The observed event yields in data (black dots) and the expectations and their uncertainties, as determined by the simultaneous fit, for all SM processes (light blue solid line with dark blue bands) are shown. For illustrative purposes only, the signal expectation (magenta solid line) in the signal region for the simplified model D (defined in section 7.2) with $m_{\tilde{g}} = 500$ GeV and $m_{LSP} = 150$ GeV is superimposed on the SM background expectation.

the total selection efficiency times acceptance for the considered signal model (16%) are included in the calculation of the limit. The dominant sources of uncertainty on the signal efficiency times acceptance are derived from systematic variations of parton distribution functions, and corrections applied to jet energies and b-tagging efficiency and mistag rates.

Figure 6 shows the observed and expected exclusion limits at 95% confidence level (CL) in the $(m_0, m_{1/2})$ plane for $\tan\beta = 10$ and $A_0 = 0$ GeV, calculated with the NLO+NLL SUSY production cross section. For this choice of parameter values, squark masses below 1250 GeV are excluded at 95% CL, as are gluino masses below the same value for the region $m_0 < 600$ GeV. In the region $600 < m_0 < 3000$ GeV, gluino masses below 700 GeV are excluded, while the squark mass in the excluded models varies in the range 1250–2500 GeV, depending on the value of m_0 . The mass limits are determined conservatively from the observed exclusion based on the theoretical production cross section minus 1σ uncertainty [55].

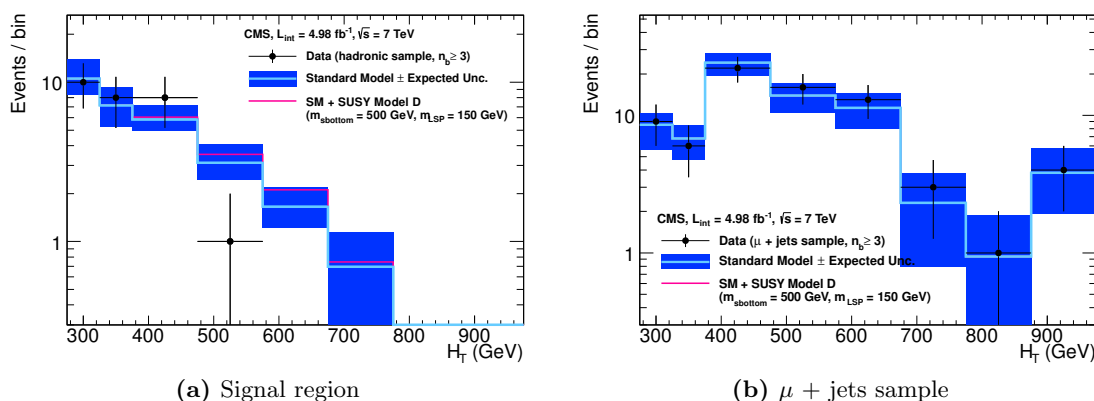


Figure 5. Comparison of the observed yields and SM expectations given by the simultaneous fit in bins of H_T for the (a) signal region and (b) $\mu + \text{jets}$ samples. Same as figure 2, except requiring at least three reconstructed b-quark jets. The observed event yields in data (black dots) and the expectations and their uncertainties, as determined by the simultaneous fit, for all SM processes (light blue solid line with dark blue bands) are shown. For illustrative purposes only, the signal expectation (magenta solid line) in the signal region for the simplified model D (defined in section 7.2) with $m_{\tilde{g}} = 500$ GeV and $m_{\text{LSP}} = 150$ GeV is superimposed on the SM background expectation.

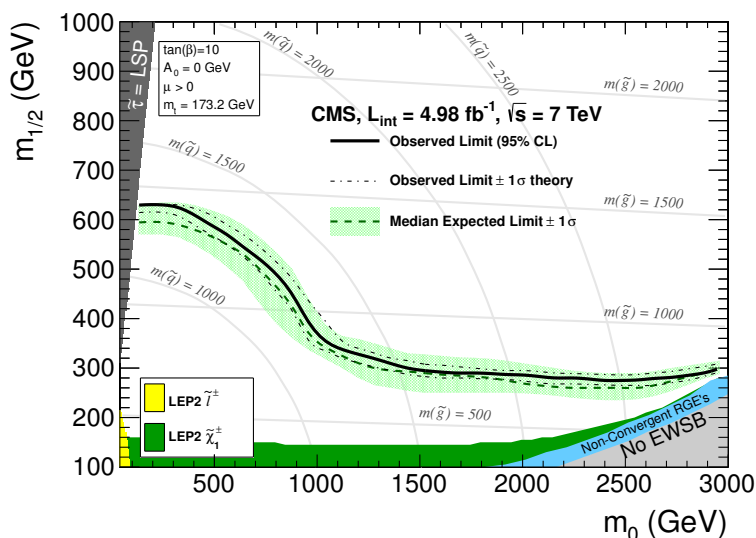


Figure 6. Exclusion contours at 95% CL in the CMSSM $(m_0, m_{1/2})$ plane ($\tan \beta = 10, A_0 = 0, \mu > 0$) calculated with NLO+NLL SUSY production cross sections and the CL_s method. The solid black line indicates the observed exclusion region. The dotted-dashed black lines represent the observed excluded region when varying the production cross section by its theoretical uncertainty. The expected median exclusion region (green dashed line) $\pm 1\sigma$ (green band) are also shown. The CMSSM template is taken from ref. [56].

Model	Production and decay modes	Figure	$m_{\tilde{q}(\tilde{g})}^{\text{best}}$ (GeV)	$m_{\text{LSP}}^{\text{best}}$ (GeV)
<i>A</i>	$pp \rightarrow \tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}^0 q\bar{q}\tilde{\chi}^0$	7a	≈ 950	≈ 400
<i>B</i>	$pp \rightarrow \tilde{q}\tilde{q} \rightarrow q\tilde{\chi}^0 \bar{q}\tilde{\chi}^0$	7b	≈ 750	≈ 275
<i>C</i>	$pp \rightarrow \tilde{t}\tilde{t} \rightarrow t\tilde{\chi}^0 \bar{t}\tilde{\chi}^0$	7c	—	—
<i>D</i>	$pp \rightarrow \tilde{b}\tilde{b} \rightarrow b\tilde{\chi}^0 \bar{b}\tilde{\chi}^0$	7d	≈ 500	≈ 175
<i>E</i>	$pp \rightarrow \tilde{g}\tilde{g} \rightarrow t\bar{t}\tilde{\chi}^0 t\bar{t}\tilde{\chi}^0$	7e	≈ 850	≈ 250
<i>F</i>	$pp \rightarrow \tilde{g}\tilde{g} \rightarrow b\bar{b}\tilde{\chi}^0 b\bar{b}\tilde{\chi}^0$	7f	≈ 1025	≈ 550

Table 2. The first three columns define the production and decay modes for various simplified models. The last two columns indicate the search sensitivity for these models, where $m_{\tilde{q}(\tilde{g})}^{\text{best}}$ and $m_{\text{LSP}}^{\text{best}}$ represent the largest mass beyond which no limit can be set for squarks/gluinos and the LSP, respectively. The exclusion range for $m_{\tilde{q}(\tilde{g})}$ is bounded from below by the kinematic region considered for each simplified model, as defined in the text. The quoted estimates are determined conservatively from the observed exclusion based on the theoretical production cross section minus 1σ uncertainty. For model *C*, the search is at the threshold of sensitivity for the considered $(m_{\tilde{q}}, m_{\text{LSP}})$ parameter space, as discussed in the text.

7.2 Interpretation with simplified models

The data observations are also interpreted using simplified models that characterise third-generation squark production and compressed spectra scenarios, where the mass difference between the primary produced sparticle (e.g. a squark or a gluino) and the LSP is rather small. The production and decay modes of the models under consideration are summarised in table 2. The simplified models *A* and *B* are used to characterise the pair production of gluinos and first- or second-generation squarks, respectively, depending on their mass as well as on the LSP mass. Simplified models *C* to *F* describe various production and decay mechanisms in the context of third-generation squarks.

Experimental uncertainties on the SM background predictions (10–40)%, the luminosity measurement (2.2%), and the total acceptance times efficiency of the selection for the considered signal model (12%–18%) are included in the calculation of the limit. Signal efficiency in the kinematic region defined by $0 < m_{\tilde{g}(\tilde{q})} - m_{\text{LSP}} < 175 \text{ GeV}$ or $m_{\tilde{g}(\tilde{q})} < 300 \text{ GeV}$ is due in part to the presence of initial-state radiation. Given the large associated uncertainties, no interpretation is provided for this kinematic region. In the case of model *E*, for which pair-produced gluinos decay to $t\bar{t}$ pairs and the LSP, the region $0 < m_{\tilde{g}} - m_{\text{LSP}} < 400 \text{ GeV}$ is not considered.

Figure 7 shows the upper limit on the cross section at 95% CL as a function of $m_{\tilde{q}}$ or $m_{\tilde{g}}$ and m_{LSP} for various simplified models. The point-to-point fluctuations are due to the finite number of pseudo-experiments used to determine the observed upper limit. The solid thick black line indicates the observed exclusion region assuming NLO+NLL SUSY cross section for squark pair production in the limit of very massive gluinos (or vice versa). The thin black lines represent the observed excluded region when varying the cross section by its theoretical uncertainty. The dashed purple lines indicate the median (thick line) $\pm 1\sigma$ (thin lines) expected exclusion regions.

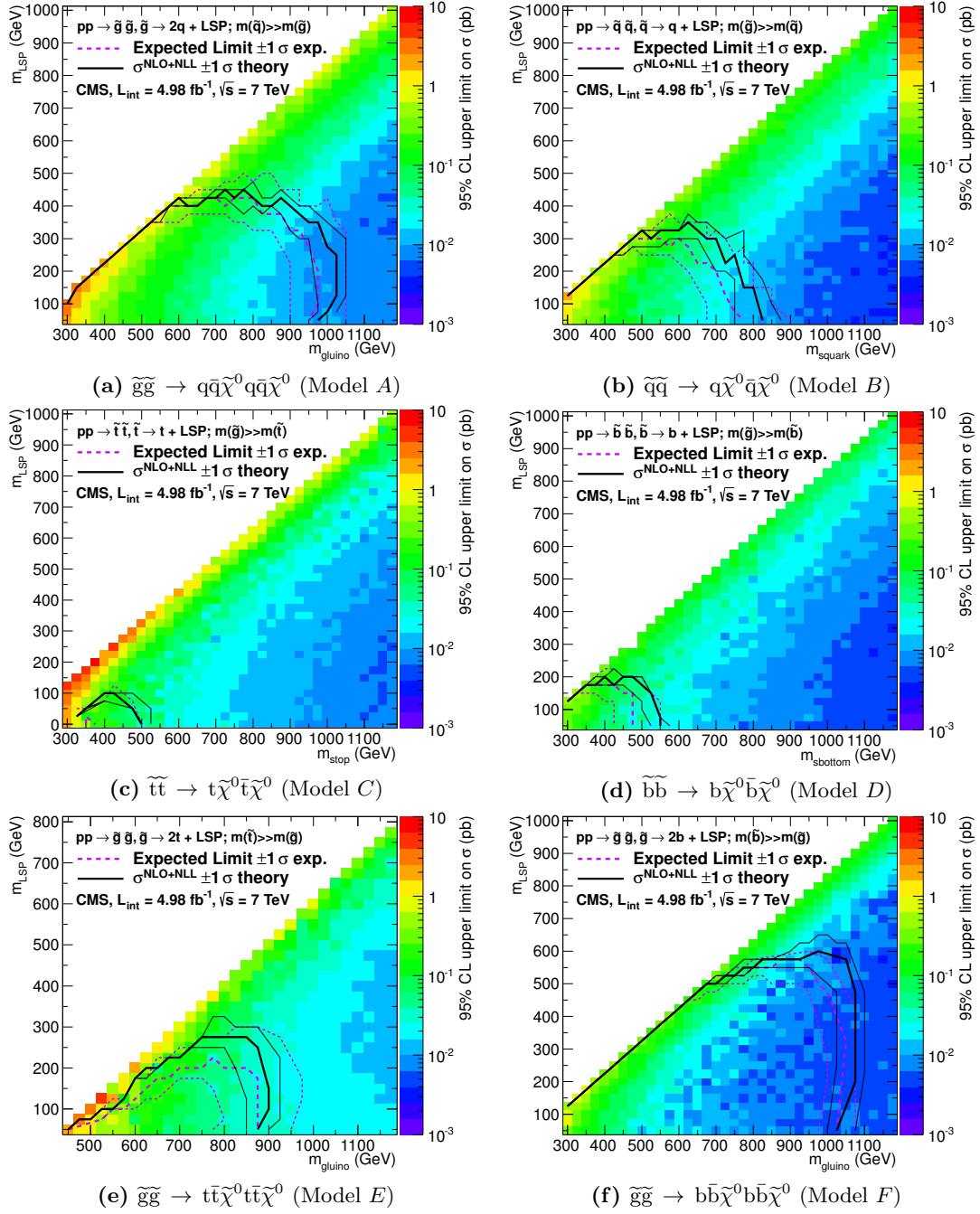


Figure 7. Upper limit on cross section at 95% CL as a function of $m_{\tilde{q}}$ or $m_{\tilde{g}}$ and m_{LSP} for various simplified models. The solid thick black line indicates the observed exclusion region assuming NLO+NLL SUSY production cross section. The thin black lines represent the observed excluded region when varying the cross section by its theoretical uncertainty. The dashed purple lines indicate the median (thick line) $\pm 1\sigma$ (thin lines) expected exclusion regions. The mass ranges considered for models C and E differ from the other models.

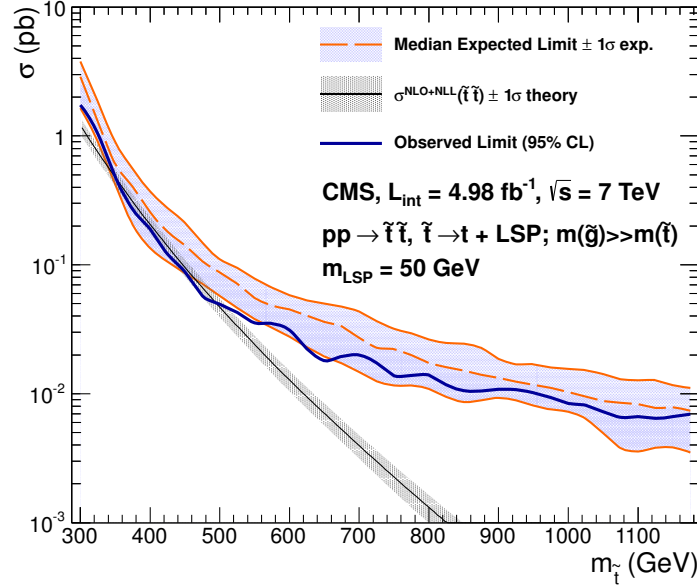


Figure 8. Excluded cross section versus top squark mass for a model in which pair-produced top squarks decay to two top quarks and two neutralinos of mass $m_{\text{LSP}} = 50$ GeV. The solid blue line indicates the observed cross section upper limit (95% CL) as a function of the top squark mass, $m_{\tilde{t}}$. The dashed orange line and blue band indicate the median expected excluded cross section with experimental uncertainties. The solid black line and grey band indicate the NLO+NLL SUSY top squark pair-production cross section and theoretical uncertainties.

The most stringent mass limits on the pair-produced particles are obtained at low LSP masses, while the limits typically weaken for compressed spectra, i.e., points close to the diagonal. In particular, for all of the considered simplified models, there is an LSP mass beyond which no limit can be set. This is illustrated in figure 7a, where the most stringent limit on the gluino mass is obtained at around 950 GeV for low LSP masses, while this limit weakens to below 900 GeV when the LSP mass reaches 350 GeV. For LSP masses above 400 GeV, no gluino masses can be excluded. Table 2 summarises these two extreme cases for models A to F. The estimates on the mass limits are determined conservatively from the observed exclusion based on the theoretical production cross section minus 1σ uncertainty.

No exclusion of direct top squark pair production (model C) assuming the NLO+NLL production cross section is expected with the analysed dataset and for LSP masses greater than 50 GeV. Figure 8 shows the observed upper limit at 95% CL on the cross section as a function of the top squark mass ($m_{\tilde{t}}$) only, for a fixed LSP mass of $m_{\text{LSP}} = 50$ GeV. Within the mass range $350 < m_{\tilde{t}} < 475$ GeV, the observed upper limit fluctuates about the theoretical production cross section minus 1σ uncertainty. This mass range is fully excluded when considering the nominal production cross section.

8 Summary

A search for supersymmetry using the CMS detector is reported, based on a data sample of pp collisions collected at $\sqrt{s} = 7$ TeV, corresponding to an integrated luminosity of $4.98 \pm 0.11 \text{ fb}^{-1}$. Final states with two or more jets and significant \cancel{E}_T , as expected from high-mass squark and gluino production and decays, have been analysed. An exclusive search has been performed in a binned signal region defined by the scalar sum of the transverse energy of jets, H_T , and the number of jets identified to originate from a bottom quark. The sum of standard model backgrounds per bin has been estimated from a simultaneous binned likelihood fit to hadronic, $\mu + \text{jets}$, $\mu\mu + \text{jets}$, and $\gamma + \text{jets}$ samples. The observed yields are found to be in agreement with the expected contributions from standard model processes. Limits in the CMSSM $(m_0, m_{1/2})$ plane for $\tan\beta = 10$, $A_0 = 0$ GeV, and $\mu > 0$ have been derived. For this choice of parameter values, gluino masses below 700 GeV are excluded at 95% CL. The exclusion increases to 1250 GeV for squarks and gluinos of comparable mass. Furthermore, exclusion limits are also set in simplified models, with a special emphasis on third generation squarks and compressed spectra scenarios. In the considered models with gluino pair production and for small LSP masses, typical exclusion limits of the gluino mass are around 1 TeV. For simplified models with squark pair production, first or second generation squarks are excluded up to around 750 GeV and bottom squarks are excluded up to around 500 GeV, again for small LSP masses. No exclusion is expected for direct pair production of top squarks that each decay to a top quark and a neutralino of mass $m_{\text{LSP}} > 50$ GeV. However, within the mass range $350 < m_{\tilde{t}} < 475$ GeV and for $m_{\text{LSP}} = 50$ GeV, the observed upper limit fluctuates about the theoretical production cross section minus 1σ uncertainty. Thus, for the simplified models under consideration, the most constraining limits on the LSP and third-generation squark masses indicate that a large range of SUSY parameter space is yet to be probed by the LHC.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centres and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: the Austrian Federal Ministry of Science and Research; the Belgian Fonds de la Recherche Scientifique, and Fonds voor Wetenschappelijk Onderzoek; the Brazilian Funding Agencies (CNPq, CAPES, FAPERJ, and FAPESP); the Bulgarian Ministry of Education, Youth and Science; CERN; the Chinese Academy of Sciences, Ministry of Science and Technology, and National Natural Science Foundation of China; the Colombian Funding Agency (COLCIENCIAS); the Croatian Ministry of Science, Education and Sport; the Research Promotion Foundation, Cyprus; the Ministry of Education and Research, Recurrent fi-

nancing contract SF0690030s09 and European Regional Development Fund, Estonia; the Academy of Finland, Finnish Ministry of Education and Culture, and Helsinki Institute of Physics; the Institut National de Physique Nucléaire et de Physique des Particules / CNRS, and Commissariat à l'Énergie Atomique et aux Énergies Alternatives / CEA, France; the Bundesministerium für Bildung und Forschung, Deutsche Forschungsgemeinschaft, and Helmholtz-Gemeinschaft Deutscher Forschungszentren, Germany; the General Secretariat for Research and Technology, Greece; the National Scientific Research Foundation, and National Office for Research and Technology, Hungary; the Department of Atomic Energy and the Department of Science and Technology, India; the Institute for Studies in Theoretical Physics and Mathematics, Iran; the Science Foundation, Ireland; the Istituto Nazionale di Fisica Nucleare, Italy; the Korean Ministry of Education, Science and Technology and the World Class University program of NRF, Korea; the Lithuanian Academy of Sciences; the Mexican Funding Agencies (CINVESTAV, CONACYT, SEP, and UASLP-FAI); the Ministry of Science and Innovation, New Zealand; the Pakistan Atomic Energy Commission; the Ministry of Science and Higher Education and the National Science Centre, Poland; the Fundação para a Ciência e a Tecnologia, Portugal; JINR (Armenia, Belarus, Georgia, Ukraine, Uzbekistan); the Ministry of Education and Science of the Russian Federation, the Federal Agency of Atomic Energy of the Russian Federation, Russian Academy of Sciences, and the Russian Foundation for Basic Research; the Ministry of Science and Technological Development of Serbia; the Secretaría de Estado de Investigación, Desarrollo e Innovación and Programa Consolider-Ingenio 2010, Spain; the Swiss Funding Agencies (ETH Board, ETH Zurich, PSI, SNF, UniZH, Canton Zurich, and SER); the National Science Council, Taipei; the Thailand Center of Excellence in Physics, the Institute for the Promotion of Teaching Science and Technology and National Electronics and Computer Technology Center; the Scientific and Technical Research Council of Turkey, and Turkish Atomic Energy Authority; the Science and Technology Facilities Council, U.K.; the US Department of Energy, and the US National Science Foundation. Individuals have received support from the Marie-Curie programme and the European Research Council (European Union); the Leventis Foundation; the A. P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the Ministry of Education, Youth and Sports (MEYS) of Czech Republic; the Council of Science and Industrial Research, India; the Compagnia di San Paolo (Torino); and the HOMING PLUS programme of Foundation for Polish Science, cofinanced from European Union, Regional Development Fund.

Open Access. This article is distributed under the terms of the Creative Commons Attribution License which permits any use, distribution and reproduction in any medium, provided the original author(s) and source are credited.

References

- [1] Y. Golfand and E. Likhtman, *Extension of the algebra of Poincaré group generators and violation of p invariance*, *JETP Lett.* **13** (1971) 323 [*Pisma Zh. Eksp. Teor. Fiz.* **13** (1971) 452] [[INSPIRE](#)].

- [2] J. Wess and B. Zumino, *Supergauge transformations in four-dimensions*, *Nucl. Phys. B* **70** (1974) 39 [INSPIRE].
- [3] H.P. Nilles, *Supersymmetry, supergravity and particle physics*, *Phys. Rept.* **110** (1984) 1 [INSPIRE].
- [4] H.E. Haber and G.L. Kane, *The search for supersymmetry: probing physics beyond the Standard Model*, *Phys. Rept.* **117** (1985) 75 [INSPIRE].
- [5] R. Barbieri, S. Ferrara and C.A. Savoy, *Gauge models with spontaneously broken local supersymmetry*, *Phys. Lett. B* **119** (1982) 343 [INSPIRE].
- [6] S. Dawson, E. Eichten and C. Quigg, *Search for supersymmetric particles in hadron-hadron collisions*, *Phys. Rev. D* **31** (1985) 1581 [INSPIRE].
- [7] E. Witten, *Dynamical breaking of supersymmetry*, *Nucl. Phys. B* **188** (1981) 513 [INSPIRE].
- [8] S. Dimopoulos and H. Georgi, *Softly broken supersymmetry and SU(5)*, *Nucl. Phys. B* **193** (1981) 150 [INSPIRE].
- [9] R. Barbieri and D. Pappadopulo, *S-particles at their naturalness limits*, *JHEP* **10** (2009) 061 [arXiv:0906.4546] [INSPIRE].
- [10] ATLAS collaboration, *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*, *Phys. Lett. B* **716** (2012) 1 [arXiv:1207.7214] [INSPIRE].
- [11] CMS collaboration, *Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC*, *Phys. Lett. B* **716** (2012) 30 [arXiv:1207.7235] [INSPIRE].
- [12] G.R. Farrar and P. Fayet, *Phenomenology of the production, decay and detection of new hadronic states associated with supersymmetry*, *Phys. Lett. B* **76** (1978) 575 [INSPIRE].
- [13] CMS collaboration, *Search for supersymmetry at the LHC in events with jets and missing transverse energy*, *Phys. Rev. Lett.* **107** (2011) 221804 [arXiv:1109.2352] [INSPIRE].
- [14] CMS collaboration, *Search for supersymmetry in pp collisions at 7 TeV in events with jets and missing transverse energy*, *Phys. Lett. B* **698** (2011) 196 [arXiv:1101.1628] [INSPIRE].
- [15] CMS collaboration, *Search for new physics with jets and missing transverse momentum in pp collisions at $\sqrt{s} = 7$ TeV*, *JHEP* **08** (2011) 155 [arXiv:1106.4503] [INSPIRE].
- [16] CMS collaboration, *Inclusive search for squarks and gluinos in pp collisions at $\sqrt{s} = 7$ TeV*, *Phys. Rev. D* **85** (2012) 012004 [arXiv:1107.1279] [INSPIRE].
- [17] CMS collaboration, *Search for supersymmetry in events with b jets and missing transverse momentum at the LHC*, *JHEP* **07** (2011) 113 [arXiv:1106.3272] [INSPIRE].
- [18] ATLAS collaboration, *Search for squarks and gluinos using final states with jets and missing transverse momentum with the ATLAS detector in $\sqrt{s} = 7$ TeV proton-proton collisions*, *Phys. Lett. B* **710** (2012) 67 [arXiv:1109.6572] [INSPIRE].
- [19] ATLAS collaboration, *Search for new phenomena in final states with large jet multiplicities and missing transverse momentum using $\sqrt{s} = 7$ TeV pp collisions with the ATLAS detector*, *JHEP* **11** (2011) 099 [arXiv:1110.2299] [INSPIRE].
- [20] ATLAS collaboration, *Search for scalar bottom pair production with the ATLAS detector in pp collisions at $\sqrt{s} = 7$ TeV*, *Phys. Rev. Lett.* **108** (2012) 181802 [arXiv:1112.3832] [INSPIRE].

- [21] ATLAS collaboration, *Search for squarks and gluinos using final states with jets and missing transverse momentum with the ATLAS detector in $\sqrt{s} = 7$ TeV proton-proton collisions*, *Phys. Lett. B* **701** (2011) 186 [[arXiv:1102.5290](#)] [[INSPIRE](#)].
- [22] A.H. Chamseddine, R.L. Arnowitt and P. Nath, *Locally supersymmetric grand unification*, *Phys. Rev. Lett.* **49** (1982) 970 [[INSPIRE](#)].
- [23] R.L. Arnowitt and P. Nath, *SUSY mass spectrum in SU(5) supergravity grand unification*, *Phys. Rev. Lett.* **69** (1992) 725 [[INSPIRE](#)].
- [24] G.L. Kane, C.F. Kolda, L. Roszkowski and J.D. Wells, *Study of constrained minimal supersymmetry*, *Phys. Rev. D* **49** (1994) 6173 [[hep-ph/9312272](#)] [[INSPIRE](#)].
- [25] J. Alwall, P. Schuster and N. Toro, *Simplified models for a first characterization of new physics at the LHC*, *Phys. Rev. D* **79** (2009) 075020 [[arXiv:0810.3921](#)] [[INSPIRE](#)].
- [26] J. Alwall, M.-P. Le, M. Lisanti and J.G. Wacker, *Model-independent jets plus missing energy searches*, *Phys. Rev. D* **79** (2009) 015005 [[arXiv:0809.3264](#)] [[INSPIRE](#)].
- [27] LHC NEW PHYSICS WORKING GROUP collaboration, D. Alves et al., *Simplified models for LHC new physics searches*, *J. Phys. G* **39** (2012) 105005 [[arXiv:1105.2838](#)] [[INSPIRE](#)].
- [28] CMS collaboration, *The CMS experiment at the CERN LHC*, 2008 *JINST* **3** S08004 [[INSPIRE](#)].
- [29] M. Cacciari, G.P. Salam and G. Soyez, *The anti- k_T jet clustering algorithm*, *JHEP* **04** (2008) 063 [[arXiv:0802.1189](#)] [[INSPIRE](#)].
- [30] CMS collaboration, *Determination of jet energy calibration and transverse momentum resolution in CMS*, 2011 *JINST* **6** P11002 [[arXiv:1107.4277](#)] [[INSPIRE](#)].
- [31] CMS collaboration, *Identification and filtering of uncharacteristic noise in the CMS hadron calorimeter*, 2010 *JINST* **5** T03014 [[arXiv:0911.4881](#)] [[INSPIRE](#)].
- [32] CMS collaboration, *Electron reconstruction and identification at $\sqrt{s} = 7$ TeV*, CMS-PAS-EGM-10-004, CERN, Geneva Switzerland (2010).
- [33] CMS collaboration, *Performance of CMS muon reconstruction in pp collision events at $\sqrt{s} = 7$ TeV*, 2012 *JINST* **7** P10002 [[arXiv:1206.4071](#)] [[INSPIRE](#)].
- [34] CMS collaboration, *Isolated photon reconstruction and identification at $\sqrt{s} = 7$ TeV*, CMS-PAS-EGM-10-006, CERN, Geneva Switzerland (2010).
- [35] CMS collaboration, *b-jet identification in the CMS experiment*, CMS-PAS-BTV-11-004, CERN, Geneva Switzerland (2012).
- [36] CMS collaboration, *Measurement of btagging efficiency using $t\bar{t}$ events*, CMS-PAS-BTV-11-003, CERN, Geneva Switzerland (2012).
- [37] L. Randall and D. Tucker-Smith, *Dijet searches for supersymmetry at the LHC*, *Phys. Rev. Lett.* **101** (2008) 221803 [[arXiv:0806.1049](#)] [[INSPIRE](#)].
- [38] Z. Bern et al., *Driving missing data at next-to-leading order*, *Phys. Rev. D* **84** (2011) 114002 [[arXiv:1106.1423](#)] [[INSPIRE](#)].
- [39] CMS collaboration, *First measurement of the cross section for top-quark pair production in proton-proton collisions at $\sqrt{s} = 7$ TeV*, *Phys. Lett. B* **695** (2011) 424 [[arXiv:1010.5994](#)] [[INSPIRE](#)].

- [40] J. Alwall et al., *MadGraph/MadEvent v4: the new web generation*, *JHEP* **09** (2007) 028 [[arXiv:0706.2334](#)] [[INSPIRE](#)].
- [41] T. Sjöstrand, S. Mrenna and P.Z. Skands, *PYTHIA 6.4 physics and manual*, *JHEP* **05** (2006) 026 [[hep-ph/0603175](#)] [[INSPIRE](#)].
- [42] GEANT4 collaboration, S. Agostinelli et al., *GEANT4: a simulation toolkit*, *Nucl. Instrum. Meth. A* **506** (2003) 250 [[INSPIRE](#)].
- [43] A.L. Read, *Presentation of search results: the CL_s technique*, *J. Phys. G* **28** (2002) 2693 [[INSPIRE](#)].
- [44] T. Junk, *Confidence level computation for combining searches with small statistics*, *Nucl. Instrum. Meth. A* **434** (1999) 435 [[hep-ex/9902006](#)] [[INSPIRE](#)].
- [45] G. Cowan, K. Cranmer, E. Gross and O. Vitells, *Asymptotic formulae for likelihood-based tests of new physics*, *Eur. Phys. J. C* **71** (2011) 1554 [[arXiv:1007.1727](#)] [[INSPIRE](#)].
- [46] W. Beenakker, R. Hopker, M. Spira and P. Zerwas, *Squark and gluino production at hadron colliders*, *Nucl. Phys. B* **492** (1997) 51 [[hep-ph/9610490](#)] [[INSPIRE](#)].
- [47] A. Kulesza and L. Motyka, *Threshold resummation for squark-antisquark and gluino-pair production at the LHC*, *Phys. Rev. Lett.* **102** (2009) 111802 [[arXiv:0807.2405](#)] [[INSPIRE](#)].
- [48] A. Kulesza and L. Motyka, *Soft gluon resummation for the production of gluino-gluino and squark-antisquark pairs at the LHC*, *Phys. Rev. D* **80** (2009) 095004 [[arXiv:0905.4749](#)] [[INSPIRE](#)].
- [49] W. Beenakker et al., *Soft-gluon resummation for squark and gluino hadroproduction*, *JHEP* **12** (2009) 041 [[arXiv:0909.4418](#)] [[INSPIRE](#)].
- [50] W. Beenakker et al., *Squark and gluino hadroproduction*, *Int. J. Mod. Phys. A* **26** (2011) 2637 [[arXiv:1105.1110](#)] [[INSPIRE](#)].
- [51] W. Beenakker, R. Hopker, M. Spira and P. Zerwas, *Squark and gluino production at hadron colliders*, *Nucl. Phys. B* **492** (1997) 51 [[hep-ph/9610490](#)] [[INSPIRE](#)].
- [52] J. Pumplin et al., *New generation of parton distributions with uncertainties from global QCD analysis*, *JHEP* **07** (2002) 012 [[hep-ph/0201195](#)] [[INSPIRE](#)].
- [53] B. Allanach, *SOFTSUSY: a program for calculating supersymmetric spectra*, *Comput. Phys. Commun.* **143** (2002) 305 [[hep-ph/0104145](#)] [[INSPIRE](#)].
- [54] CMS collaboration, *Absolute calibration of the luminosity measurement at CMS: winter 2012 update*, *CMS-PAS-SMP-12-008*, CERN, Geneva Switzerland (2012).
- [55] M. Krämer et al., *Supersymmetry production cross sections in pp collisions at $\sqrt{s} = 7$ TeV*, [arXiv:1206.2892](#) [[INSPIRE](#)].
- [56] K. Matchev and R. Remington, *Updated templates for the interpretation of LHC results on supersymmetry in the context of mSUGRA*, [arXiv:1202.6580](#) [[INSPIRE](#)].

The CMS collaboration

Yerevan Physics Institute, Yerevan, Armenia

S. Chatrchyan, V. Khachatryan, A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik der OeAW, Wien, Austria

W. Adam, E. Aguilo, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan¹, M. Friedl, R. Frühwirth¹, V.M. Ghete, J. Hammer, N. Hörmann, J. Hrubec, M. Jeitler¹, W. Kiesenhofer, V. Knünz, M. Krammer¹, I. Krätschmer, D. Liko, I. Mikulec, M. Pernicka[†], B. Rahbaran, C. Rohringer, H. Rohringer, R. Schöffbeck, J. Strauss, A. Taurok, W. Waltenberger, G. Walzel, E. Widl, C.-E. Wulz¹

National Centre for Particle and High Energy Physics, Minsk, Belarus

V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium

M. Bansal, S. Bansal, T. Cornelis, E.A. De Wolf, X. Janssen, S. Luyckx, L. Mucibello, S. Ochesanu, B. Roland, R. Rougny, M. Selvaggi, Z. Staykova, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel, A. Van Spilbeeck

Vrije Universiteit Brussel, Brussel, Belgium

F. Blekman, S. Blyweert, J. D'Hondt, R. Gonzalez Suarez, A. Kalogeropoulos, M. Maes, A. Olbrechts, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Villella

Université Libre de Bruxelles, Bruxelles, Belgium

B. Clerbaux, G. De Lentdecker, V. Dero, A.P.R. Gay, T. Hreus, A. Léonard, P.E. Marage, A. Mohammadi, T. Reis, L. Thomas, G. Vander Marcken, C. Vander Velde, P. Vanlaer, J. Wang

Ghent University, Ghent, Belgium

V. Adler, K. Beernaert, A. Cimmino, S. Costantini, G. Garcia, M. Grunewald, B. Klein, J. Lellouch, A. Marinov, J. Mccartin, A.A. Ocampo Rios, D. Ryckbosch, N. Strobbe, F. Thyssen, M. Tytgat, P. Verwilligen, S. Walsh, E. Yazgan, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium

S. Basegmez, G. Bruno, R. Castello, L. Ceard, C. Delaere, T. du Pree, D. Favart, L. Forthomme, A. Giammanco², J. Hollar, V. Lemaitre, J. Liao, O. Militaru, C. Nuttens, D. Pagano, A. Pin, K. Piotrkowski, N. Schul, J.M. Vizan Garcia

Université de Mons, Mons, Belgium

N. Bely, T. Caebergs, E. Daubie, G.H. Hammad

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

G.A. Alves, M. Correa Martins Junior, D. De Jesus Damiao, T. Martins, M.E. Pol, M.H.G. Souza

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

W.L. Aldá Júnior, W. Carvalho, A. Custódio, E.M. Da Costa, C. De Oliveira Martins, S. Fonseca De Souza, D. Matos Figueiredo, L. Mundim, H. Nogima, V. Oguri, W.L. Prado Da Silva, A. Santoro, L. Soares Jorge, A. Sznajder

Instituto de Fisica Teorica, Universidade Estadual Paulista, Sao Paulo, Brazil

T.S. Anjos³, C.A. Bernardes³, F.A. Dias⁴, T.R. Fernandez Perez Tomei, E.M. Gregores³, C. Lagana, F. Marinho, P.G. Mercadante³, S.F. Novaes, Sandra S. Padula

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

V. Genchev⁵, P. Iaydjiev⁵, S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, V. Tcholakov, R. Trayanov, M. Vutova

University of Sofia, Sofia, Bulgaria

A. Dimitrov, R. Hadjiiska, V. Kozhuharov, L. Litov, B. Pavlov, P. Petkov

Institute of High Energy Physics, Beijing, China

J.G. Bian, G.M. Chen, H.S. Chen, C.H. Jiang, D. Liang, S. Liang, X. Meng, J. Tao, J. Wang, X. Wang, Z. Wang, H. Xiao, M. Xu, J. Zang, Z. Zhang

State Key Lab. of Nucl. Phys. and Tech., Peking University, Beijing, China

C. Asawatangtrakuldee, Y. Ban, Y. Guo, W. Li, S. Liu, Y. Mao, S.J. Qian, H. Teng, D. Wang, L. Zhang, W. Zou

Universidad de Los Andes, Bogota, Colombia

C. Avila, J.P. Gomez, B. Gomez Moreno, A.F. Osorio Oliveros, J.C. Sanabria

Technical University of Split, Split, Croatia

N. Godinovic, D. Lelas, R. Plestina⁶, D. Polic, I. Puljak⁵

University of Split, Split, Croatia

Z. Antunovic, M. Kovac

Institute Rudjer Boskovic, Zagreb, Croatia

V. Brigljevic, S. Duric, K. Kadija, J. Luetic, S. Morovic

University of Cyprus, Nicosia, Cyprus

A. Attikis, M. Galanti, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis

Charles University, Prague, Czech Republic

M. Finger, M. Finger Jr.

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt

Y. Assran⁷, S. Elgammal⁸, A. Ellithi Kamel⁹, M.A. Mahmoud¹⁰, A. Radi^{11,12}

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

M. Kadastik, M. Müntel, M. Raidal, L. Rebane, A. Tiko

Department of Physics, University of Helsinki, Helsinki, Finland

P. Eerola, G. Fedi, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland

J. Härkönen, A. Heikkinen, V. Karimäki, R. Kinnunen, M.J. Kortelainen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, T. Peltola, E. Tuominen, J. Tuominiemi, E. Tuovinen, D. Ungaro, L. Wendland

Lappeenranta University of Technology, Lappeenranta, Finland

K. Banzuzi, A. Karjalainen, A. Korpela, T. Tuuva

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France

M. Besancon, S. Choudhury, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, J. Malcles, L. Millischer, A. Nayak, J. Rander, A. Rosowsky, I. Shreyber, M. Titov

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France

S. Baffioni, F. Beaudette, L. Benhabib, L. Bianchini, M. Bluj¹³, C. Broutin, P. Busson, C. Charlot, N. Daci, T. Dahms, L. Dobrzynski, R. Granier de Cassagnac, M. Haguenaue, P. Miné, C. Mironov, I.N. Naranjo, M. Nguyen, C. Ochando, P. Paganini, D. Sabes, R. Salerno, Y. Sirois, C. Veelken, A. Zabi

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France

J.-L. Agram¹⁴, J. Andrea, D. Bloch, D. Bodin, J.-M. Brom, M. Cardaci, E.C. Chabert, C. Collard, E. Conte¹⁴, F. Drouhin¹⁴, C. Ferro, J.-C. Fontaine¹⁴, D. Gelé, U. Goerlach, P. Juillot, A.-C. Le Bihan, P. Van Hove

Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France, Villeurbanne, France

F. Fassi, D. Mercier

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France

S. Beauceron, N. Beaupere, O. Bondu, G. Boudoul, J. Chasserat, R. Chierici⁵, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, B. Ille, T. Kurca, M. Lethuillier, L. Mirabito, S. Perries, L. Sgandurra, V. Sordini, Y. Tschudi, P. Verdier, S. Viret

Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia

Z. Tsamalaidze¹⁵

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany

G. Anagnostou, C. Autermann, S. Beranek, M. Edelhoff, L. Feld, N. Heracleous, O. Hindrichs, R. Jussen, K. Klein, J. Merz, A. Ostapchuk, A. Perieanu, F. Raupach, J. Sammet, S. Schael, D. Sprenger, H. Weber, B. Wittmer, V. Zhukov¹⁶

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

M. Ata, J. Caudron, E. Dietz-Laursonn, D. Duchardt, M. Erdmann, R. Fischer, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, D. Klingebiel, P. Kreuzer, M. Merschmeyer, A. Meyer, M. Olschewski, P. Papacz, H. Pieta, H. Reithler, S.A. Schmitz, L. Sonnenschein, J. Steggemann, D. Teyssier, M. Weber

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany

M. Bontenackels, V. Cherepanov, Y. Erdogan, G. Flügge, H. Geenen, M. Geisler, W. Haj Ahmad, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, J. Lingemann⁵, A. Nowack, L. Perchalla, O. Pooth, P. Sauerland, A. Stahl

Deutsches Elektronen-Synchrotron, Hamburg, Germany

M. Aldaya Martin, J. Behr, W. Behrenhoff, U. Behrens, M. Bergholz¹⁷, A. Bethani, K. Borras, A. Burgmeier, A. Cakir, L. Calligaris, A. Campbell, E. Castro, F. Costanza, D. Dammann, C. Diez Pardos, G. Eckerlin, D. Eckstein, G. Flucke, A. Geiser, I. Glushkov, P. Gunnellini, S. Habib, J. Hauk, G. Hellwig, H. Jung, M. Kasemann, P. Katsas, C. Kleinwort, H. Kluge, A. Knutsson, M. Krämer, D. Krücker, E. Kuznetsova, W. Lange, W. Lohmann¹⁷, B. Lutz, R. Mankel, I. Marfin, M. Marienfeld, I.-A. Melzer-Pellmann, A.B. Meyer, J. Mnich, A. Mussgiller, S. Naumann-Emme, O. Novgorodova, J. Olzem, H. Perrey, A. Petrukhin, D. Pitzl, A. Raspereza, P.M. Ribeiro Cipriano, C. Riedl, E. Ron, M. Rosin, J. Salfeld-Nebgen, R. Schmidt¹⁷, T. Schoerner-Sadenius, N. Sen, A. Spiridonov, M. Stein, R. Walsh, C. Wissing

University of Hamburg, Hamburg, Germany

V. Blobel, J. Draeger, H. Enderle, J. Erfle, U. Gebbert, M. Görner, T. Hermanns, R.S. Höing, K. Kaschube, G. Kaussen, H. Kirschenmann, R. Klanner, J. Lange, B. Mura, F. Nowak, T. Peiffer, N. Pietsch, D. Rathjens, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, A. Schmidt, M. Schröder, T. Schum, M. Seidel, V. Sola, H. Stadie, G. Steinbrück, J. Thomsen, L. Vanelderen

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

C. Barth, J. Berger, C. Böser, T. Chwalek, W. De Boer, A. Descroix, A. Dierlamm, M. Feindt, M. Guthoff⁵, C. Hackstein, F. Hartmann, T. Hauth⁵, M. Heinrich, H. Held, K.H. Hoffmann, U. Husemann, I. Katkov¹⁶, J.R. Komaragiri, P. Lobelle Pardo, D. Martschei, S. Mueller, Th. Müller, M. Niegel, A. Nürnberg, O. Oberst, A. Oehler, J. Ott, G. Quast, K. Rabbertz, F. Ratnikov, N. Ratnikova, S. Röcker, F.-P. Schilling, G. Schott, H.J. Simonis, F.M. Stober, D. Troendle, R. Ulrich, J. Wagner-Kuhr, S. Wayand, T. Weiler, M. Zeise

Institute of Nuclear Physics "Demokritos", Aghia Paraskevi, Greece

G. Daskalakis, T. Geralis, S. Kesisoglou, A. Kyriakis, D. Loukas, I. Manolakos, A. Markou, C. Markou, C. Mavrommatis, E. Ntomari

University of Athens, Athens, Greece

L. Gouskos, T.J. Mertzimekis, A. Panagiotou, N. Saoulidou

University of Ioánnina, Ioánnina, Greece

I. Evangelou, C. Foudas, P. Kokkas, N. Manthos, I. Papadopoulos, V. Patras

KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary

G. Bencze, C. Hajdu, P. Hidas, D. Horvath¹⁸, F. Sikler, V. Veszpremi, G. Vesztergombi¹⁹

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni, S. Czellar, J. Molnar, J. Palinkas, Z. Szillasi

University of Debrecen, Debrecen, Hungary

J. Karancsi, P. Raics, Z.L. Trocsanyi, B. Ujvari

Panjab University, Chandigarh, India

S.B. Beri, V. Bhatnagar, N. Dhingra, R. Gupta, M. Kaur, M.Z. Mehta, N. Nishu, L.K. Saini, A. Sharma, J.B. Singh

University of Delhi, Delhi, India

Ashok Kumar, Arun Kumar, S. Ahuja, A. Bhardwaj, B.C. Choudhary, S. Malhotra, M. Naimuddin, K. Ranjan, V. Sharma, R.K. Shivpuri

Saha Institute of Nuclear Physics, Kolkata, India

S. Banerjee, S. Bhattacharya, S. Dutta, B. Gomber, Sa. Jain, Sh. Jain, R. Khurana, S. Sarkar, M. Sharan

Bhabha Atomic Research Centre, Mumbai, India

A. Abdulsalam, R.K. Choudhury, D. Dutta, S. Kailas, V. Kumar, P. Mehta, A.K. Mohanty⁵, L.M. Pant, P. Shukla

Tata Institute of Fundamental Research - EHEP, Mumbai, India

T. Aziz, S. Ganguly, M. Guchait²⁰, M. Maity²¹, G. Majumder, K. Mazumdar, G.B. Mohanty, B. Parida, K. Sudhakar, N. Wickramage

Tata Institute of Fundamental Research - HECR, Mumbai, India

S. Banerjee, S. Dugad

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran

H. Arfaei²², H. Bakhshiansohi, S.M. Etesami²³, A. Fahim²², M. Hashemi, H. Hesari, A. Jafari, M. Khakzad, M. Mohammadi Najafabadi, S. Paktinat Mehdiabadi, B. Safarzadeh²⁴, M. Zeinali

INFN Sezione di Bari ^a, Università di Bari ^b, Politecnico di Bari ^c, Bari, Italy

M. Abbrescia^{a,b}, L. Barbone^{a,b}, C. Calabria^{a,b,5}, S.S. Chhibra^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, N. De Filippis^{a,c,5}, M. De Palma^{a,b}, L. Fiore^a, G. Iaselli^{a,c}, L. Lusito^{a,b}, G. Maggi^{a,c}, M. Maggi^a, B. Marangelli^{a,b}, S. My^{a,c}, S. Nuzzo^{a,b}, N. Pacifico^{a,b}, A. Pompili^{a,b}, G. Pugliese^{a,c}, G. Selvaggi^{a,b}, L. Silvestris^a, G. Singh^{a,b}, R. Venditti^{a,b}, G. Zito^a

INFN Sezione di Bologna ^a, Università di Bologna ^b, Bologna, Italy

G. Abbiendi^a, A.C. Benvenuti^a, D. Bonacorsi^{a,b}, S. Braibant-Giacomelli^{a,b}, L. Brigliadori^{a,b}, P. Capiluppi^{a,b}, A. Castro^{a,b}, F.R. Cavallo^a, M. Cuffiani^{a,b},

G.M. Dallavalle^a, F. Fabbri^a, A. Fanfani^{a,b}, D. Fasanella^{a,b,5}, P. Giacomelli^a, C. Grandi^a, L. Guiducci^{a,b}, S. Marcellini^a, G. Masetti^a, M. Meneghelli^{a,b,5}, A. Montanari^a, F.L. Navarria^{a,b}, F. Odorici^a, A. Perrotta^a, F. Primavera^{a,b}, A.M. Rossi^{a,b}, T. Rovelli^{a,b}, G.P. Siroli^{a,b}, R. Travaglini^{a,b}

INFN Sezione di Catania ^a, Università di Catania ^b, Catania, Italy

S. Albergo^{a,b}, G. Cappello^{a,b}, M. Chiorboli^{a,b}, S. Costa^{a,b}, R. Potenza^{a,b}, A. Tricomi^{a,b}, C. Tuve^{a,b}

INFN Sezione di Firenze ^a, Università di Firenze ^b, Firenze, Italy

G. Barbagli^a, V. Ciulli^{a,b}, C. Civinini^a, R. D'Alessandro^{a,b}, E. Focardi^{a,b}, S. Frosali^{a,b}, E. Gallo^a, S. Gonzi^{a,b}, M. Meschini^a, S. Paoletti^a, G. Sguazzoni^a, A. Tropiano^{a,b}

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi, S. Bianco, S. Colafranceschi²⁵, F. Fabbri, D. Piccolo

INFN Sezione di Genova ^a, Università di Genova ^b, Genova, Italy

P. Fabbriatore^a, R. Musenich^a, S. Tosi^{a,b}

INFN Sezione di Milano-Bicocca ^a, Università di Milano-Bicocca ^b, Milano, Italy

A. Benaglia^{a,b}, F. De Guio^{a,b}, L. Di Matteo^{a,b,5}, S. Fiorendi^{a,b}, S. Gennai^{a,5}, A. Ghezzi^{a,b}, S. Malvezzi^a, R.A. Manzoni^{a,b}, A. Martelli^{a,b}, A. Massironi^{a,b,5}, D. Menasce^a, L. Moroni^a, M. Paganoni^{a,b}, D. Pedrini^a, S. Ragazzi^{a,b}, N. Redaelli^a, S. Sala^a, T. Tabarelli de Fatis^{a,b}

INFN Sezione di Napoli ^a, Università di Napoli "Federico II" ^b, Napoli, Italy

S. Buontempo^a, C.A. Carrillo Montoya^a, N. Cavallo^{a,26}, A. De Cosa^{a,b,5}, O. Dogangun^{a,b}, F. Fabozzi^{a,26}, A.O.M. Iorio^{a,b}, L. Lista^a, S. Meola^{a,27}, M. Merola^{a,b}, P. Paolucci^{a,5}

INFN Sezione di Padova ^a, Università di Padova ^b, Università di Trento (Trento) ^c, Padova, Italy

P. Azzi^a, N. Bacchetta^{a,5}, P. Bellan^{a,b}, D. Bisello^{a,b}, A. Branca^{a,b,5}, R. Carlin^{a,b}, P. Checchia^a, T. Dorigo^a, U. Dosselli^a, F. Gasparini^{a,b}, U. Gasparini^{a,b}, A. Gozzelino^a, K. Kanishchev^{a,c}, S. Lacaprara^a, I. Lazzizzera^{a,c}, M. Margoni^{a,b}, A.T. Meneguzzo^{a,b}, M. Nespolo^{a,5}, J. Pazzini^{a,b}, P. Ronchese^{a,b}, F. Simonetto^{a,b}, E. Torassa^a, S. Vanini^{a,b}, P. Zotto^{a,b}, G. Zumerle^{a,b}

INFN Sezione di Pavia ^a, Università di Pavia ^b, Pavia, Italy

M. Gabusi^{a,b}, S.P. Ratti^{a,b}, C. Riccardi^{a,b}, P. Torre^{a,b}, P. Vitulo^{a,b}

INFN Sezione di Perugia ^a, Università di Perugia ^b, Perugia, Italy

M. Biasini^{a,b}, G.M. Bilei^a, L. Fanò^{a,b}, P. Lariccia^{a,b}, G. Mantovani^{a,b}, M. Menichelli^a, A. Nappi^{a,b†}, F. Romeo^{a,b}, A. Saha^a, A. Santocchia^{a,b}, A. Spiezia^{a,b}, S. Taroni^{a,b}

INFN Sezione di Pisa ^a, Università di Pisa ^b, Scuola Normale Superiore di Pisa ^c, Pisa, Italy

P. Azzurri^{a,c}, G. Bagliesi^a, J. Bernardini^a, T. Boccali^a, G. Broccolo^{a,c}, R. Castaldi^a, R.T. D'Agnolo^{a,c,5}, R. Dell'Orso^a, F. Fiori^{a,b,5}, L. Foà^{a,c}, A. Giassi^a, A. Kraan^a,

F. Ligabue^{a,c}, T. Lomtadze^a, L. Martini^{a,28}, A. Messineo^{a,b}, F. Palla^a, A. Rizzi^{a,b}, A.T. Serban^{a,29}, P. Spagnolo^a, P. Squillacioti^{a,5}, R. Tenchini^a, G. Tonelli^{a,b}, A. Venturi^a, P.G. Verдини^a

INFN Sezione di Roma ^a, Università di Roma ^b, Roma, Italy

L. Barone^{a,b}, F. Cavallari^a, D. Del Re^{a,b}, M. Diemoz^a, C. Fanelli^{a,b}, M. Grassi^{a,b,5}, E. Longo^{a,b}, P. Meridiani^{a,5}, F. Micheli^{a,b}, S. Nourbakhsh^{a,b}, G. Organtini^{a,b}, R. Paramatti^a, S. Rahatlou^{a,b}, M. Sigamani^a, L. Soffi^{a,b}

INFN Sezione di Torino ^a, Università di Torino ^b, Università del Piemonte Orientale (Novara) ^c, Torino, Italy

N. Amapane^{a,b}, R. Arcidiacono^{a,c}, S. Argiro^{a,b}, M. Arneodo^{a,c}, C. Biino^a, N. Cartiglia^a, M. Costa^{a,b}, N. Demaria^a, C. Mariotti^{a,5}, S. Maselli^a, E. Migliore^{a,b}, V. Monaco^{a,b}, M. Musich^{a,5}, M.M. Obertino^{a,c}, N. Pastrone^a, M. Pelliccioni^a, A. Potenza^{a,b}, A. Romero^{a,b}, M. Ruspa^{a,c}, R. Sacchi^{a,b}, A. Solano^{a,b}, A. Staiano^a, A. Vilela Pereira^a

INFN Sezione di Trieste ^a, Università di Trieste ^b, Trieste, Italy

S. Belforte^a, V. Candelise^{a,b}, M. Casarsa^a, F. Cossutti^a, G. Della Ricca^{a,b}, B. Gobbo^a, M. Marone^{a,b,5}, D. Montanino^{a,b,5}, A. Penzo^a, A. Schizzi^{a,b}

Kangwon National University, Chunchon, Korea

S.G. Heo, T.Y. Kim, S.K. Nam

Kyungpook National University, Daegu, Korea

S. Chang, D.H. Kim, G.N. Kim, D.J. Kong, H. Park, S.R. Ro, D.C. Son, T. Son

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea

J.Y. Kim, Zero J. Kim, S. Song

Korea University, Seoul, Korea

S. Choi, D. Gyun, B. Hong, M. Jo, H. Kim, T.J. Kim, K.S. Lee, D.H. Moon, S.K. Park

University of Seoul, Seoul, Korea

M. Choi, J.H. Kim, C. Park, I.C. Park, S. Park, G. Ryu

Sungkyunkwan University, Suwon, Korea

Y. Cho, Y. Choi, Y.K. Choi, J. Goh, M.S. Kim, E. Kwon, B. Lee, J. Lee, S. Lee, H. Seo, I. Yu

Vilnius University, Vilnius, Lithuania

M.J. Bilinskas, I. Grigelionis, M. Janulis, A. Juodagalvis

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz, R. Lopez-Fernandez, R. Magaña Villalba, J. Martínez-Ortega, A. Sánchez-Hernández, L.M. Villasenor-Cendejas

Universidad Iberoamericana, Mexico City, Mexico

S. Carrillo Moreno, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

H.A. Salazar Ibarguen

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico

E. Casimiro Linares, A. Morelos Pineda, M.A. Reyes-Santos

University of Auckland, Auckland, New Zealand

D. Krofcheck

University of Canterbury, Christchurch, New Zealand

A.J. Bell, P.H. Butler, R. Doesburg, S. Reucroft, H. Silverwood

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan

M. Ahmad, M.H. Ansari, M.I. Asghar, H.R. Hoorani, S. Khalid, W.A. Khan, T. Khurshid, S. Qazi, M.A. Shah, M. Shoaib

National Centre for Nuclear Research, Swierk, Poland

H. Bialkowska, B. Boimska, T. Frueboes, R. Gokieli, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, G. Wrochna, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland

G. Brona, K. Bunkowski, M. Cwiok, W. Dominik, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal

N. Almeida, P. Bargassa, A. David, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro, J. Seixas, J. Varela, P. Vischia

Joint Institute for Nuclear Research, Dubna, Russia

P. Bunin, M. Gavrilenko, I. Golutvin, V. Karjavin, V. Konoplyanikov, G. Kozlov, A. Lanev, A. Malakhov, P. Moisenz, V. Palichik, V. Pereygin, M. Savina, S. Shmatov, S. Shulha, V. Smirnov, A. Volodko, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia

S. Evstyukhin, V. Golovtsov, Y. Ivanov, V. Kim, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev, An. Vorobyev

Institute for Nuclear Research, Moscow, Russia

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, M. Kirsanov, N. Krasnikov, V. Matveev, A. Pashenkov, D. Tliso, A. Toropin

Institute for Theoretical and Experimental Physics, Moscow, Russia

V. Epshteyn, M. Erofeeva, V. Gavrilov, M. Kossov, N. Lychkovskaya, V. Popov, G. Safronov, S. Semenov, V. Stolin, E. Vlasov, A. Zhokin

Moscow State University, Moscow, Russia

A. Belyaev, E. Boos, M. Dubinin⁴, L. Dudko, A. Ershov, A. Gribushin, V. Klyukhin, O. Kodolova, I. Lokhtin, A. Markina, S. Obraztsov, M. Perfilov, S. Petrushanko, A. Popov, L. Sarycheva[†], V. Savrin, A. Snigirev

P.N. Lebedev Physical Institute, Moscow, Russia

V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Leonidov, G. Mesyats, S.V. Rusakov, A. Vinogradov

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia

I. Azhgirey, I. Bayshev, S. Bitioukov, V. Grishin⁵, V. Kachanov, D. Konstantinov, V. Krychkin, V. Petrov, R. Ryutin, A. Sobol, L. Tourchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia

P. Adzic³⁰, M. Djordjevic, M. Ekmedzic, D. Krpic³⁰, J. Milosevic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain

M. Aguilar-Benitez, J. Alcaraz Maestre, P. Arce, C. Battilana, E. Calvo, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, D. Domínguez Vázquez, C. Fernandez Bedoya, J.P. Fernández Ramos, A. Ferrando, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, G. Merino, J. Puerta Pelayo, A. Quintario Olmeda, I. Redondo, L. Romero, J. Santaolalla, M.S. Soares, C. Willmott

Universidad Autónoma de Madrid, Madrid, Spain

C. Albajar, G. Codispoti, J.F. de Trocóniz

Universidad de Oviedo, Oviedo, Spain

H. Brun, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, L. Lloret Iglesias, J. Piedra Gomez

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, S.H. Chuang, J. Duarte Campderros, M. Felcini³¹, M. Fernandez, G. Gomez, J. Gonzalez Sanchez, A. Graziano, C. Jorda, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, I. Vila, R. Vilar Cortabitarte

CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo, E. Auffray, G. Auzinger, M. Bachtis, P. Baillon, A.H. Ball, D. Barney, J.F. Benitez, C. Bernet⁶, G. Bianchi, P. Bloch, A. Bocci, A. Bonato, C. Botta, H. Breuker, T. Camporesi, G. Cerminara, T. Christiansen, J.A. Coarasa Perez, D. D'Enterria,

A. Dabrowski, A. De Roeck, S. Di Guida, M. Dobson, N. Dupont-Sagorin, A. Elliott-Peisert, B. Frisch, W. Funk, G. Georgiou, M. Giffels, D. Gigi, K. Gill, D. Giordano, M. Girone, M. Giunta, F. Glege, R. Gomez-Reino Garrido, P. Govoni, S. Gowdy, R. Guida, M. Hansen, P. Harris, C. Hartl, J. Harvey, B. Hegner, A. Hinzmann, V. Innocente, P. Janot, K. Kaadze, E. Karavakis, K. Kousouris, P. Lecoq, Y.-J. Lee, P. Lenzi, C. Lourenço, N. Magini, T. Mäki, M. Malberti, L. Malgeri, M. Mannelli, L. Masetti, F. Meijers, S. Mersi, E. Meschi, R. Moser, M.U. Mozer, M. Mulders, P. Musella, E. Nesvold, T. Orimoto, L. Orsini, E. Palencia Cortezon, E. Perez, L. Perrozzi, A. Petrilli, A. Pfeiffer, M. Pierini, M. Pimiä, D. Piparo, G. Polese, L. Quertenmont, A. Racz, W. Reece, J. Rodrigues Antunes, G. Rolandi³², C. Rovelli³³, M. Rovere, H. Sakulin, F. Santanastasio, C. Schäfer, C. Schwick, I. Segoni, S. Sekmen, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas³⁴, D. Spiga, A. Tsirou, G.I. Veres¹⁹, J.R. Vlimant, H.K. Wöhri, S.D. Worm³⁵, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

W. Bertl, K. Deiters, W. Erdmann, K. Gabathuler, R. Horisberger, Q. Ingram, H.C. Kaestli, S. König, D. Kotlinski, U. Langenegger, F. Meier, D. Renker, T. Rohe, J. Sibille³⁶

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

L. Bäni, P. Bortignon, M.A. Buchmann, B. Casal, N. Chanon, A. Deisher, G. Dissertori, M. Dittmar, M. Donegà, M. Dünser, J. Eugster, K. Freudenreich, C. Grab, D. Hits, P. Lecomte, W. Lustermann, A.C. Marini, P. Martinez Ruiz del Arbol, N. Mohr, F. Moortgat, C. Nägeli³⁷, P. Nef, F. Nessi-Tedaldi, F. Pandolfi, L. Pape, F. Pauss, M. Peruzzi, F.J. Ronga, M. Rossini, L. Sala, A.K. Sanchez, A. Starodumov³⁸, B. Stieger, M. Takahashi, L. Tauscher[†], A. Thea, K. Theofilatos, D. Treille, C. Urscheler, R. Wallny, H.A. Weber, L. Wehrli

Universität Zürich, Zurich, Switzerland

C. AMSLER, V. Chiochia, S. De Visscher, C. Favaro, M. Ivova Rikova, B. Millan Mejias, P. Otiougova, P. Robmann, H. Snoek, S. Tupputi, M. Verzetti

National Central University, Chung-Li, Taiwan

Y.H. Chang, K.H. Chen, C.M. Kuo, S.W. Li, W. Lin, Z.K. Liu, Y.J. Lu, D. Mekterovic, A.P. Singh, R. Volpe, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan

P. Bartalini, P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, C. Dietz, U. Grundler, W.-S. Hou, Y. Hsiung, K.Y. Kao, Y.J. Lei, R.-S. Lu, D. Majumder, E. Petrakou, X. Shi, J.G. Shiu, Y.M. Tzeng, X. Wan, M. Wang

Chulalongkorn University, Bangkok, Thailand

B. Asavapibhop, N. Srimanobhas

Cukurova University, Adana, Turkey

A. Adiguzel, M.N. Bakirci³⁹, S. Cerci⁴⁰, C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, E. Gurpinar, I. Hos, E.E. Kangal, T. Karaman, G. Karapinar⁴¹, A. Kayis

Topaksu, G. Onengut, K. Ozdemir, S. Ozturk⁴², A. Polatoz, K. Sogut⁴³, D. Sunar Cerci⁴⁰, B. Tali⁴⁰, H. Topakli³⁹, L.N. Vergili, M. Vergili

Middle East Technical University, Physics Department, Ankara, Turkey

I.V. Akin, T. Aliev, B. Bilin, S. Bilmis, M. Deniz, H. Gamsizkan, A.M. Guler, K. Ocalan, A. Ozpineci, M. Serin, R. Sever, U.E. Surat, M. Yalvac, E. Yildirim, M. Zeyrek

Bogazici University, Istanbul, Turkey

E. Gülmez, B. Isildak⁴⁴, M. Kaya⁴⁵, O. Kaya⁴⁵, S. Ozkorucuklu⁴⁶, N. Sonmez⁴⁷

Istanbul Technical University, Istanbul, Turkey

K. Cankocak

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine

L. Levchuk

University of Bristol, Bristol, United Kingdom

F. Bostock, J.J. Brooke, E. Clement, D. Cussans, H. Flacher, R. Frazier, J. Goldstein, M. Grimes, G.P. Heath, H.F. Heath, L. Kreczko, C. Lucas, Z. Meng, S. Metson, D.M. Newbold³⁵, K. Nirunpong, A. Poll, S. Senkin, V.J. Smith, T. Williams

Rutherford Appleton Laboratory, Didcot, United Kingdom

L. Basso⁴⁸, K.W. Bell, A. Belyaev⁴⁸, C. Brew, R.M. Brown, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Jackson, B.W. Kennedy, E. Olaiya, D. Petyt, B.C. Radburn-Smith, C.H. Shepherd-Themistocleous, I.R. Tomalin, W.J. Womersley

Imperial College, London, United Kingdom

R. Bainbridge, G. Ball, R. Beuselinck, O. Buchmuller, D.L. Burton, D. Colling, N. Cripps, M. Cutajar, P. Dauncey, G. Davies, M. Della Negra, W. Ferguson, J. Fulcher, D. Futyan, A. Gilbert, A. Guneratne Bryer, G. Hall, Z. Hatherell, J. Hays, G. Iles, M. Jarvis, G. Karapostoli, L. Lyons, A.-M. Magnan, J. Marrouche, B. Mathias, R. Nandi, J. Nash, A. Nikitenko³⁸, A. Papageorgiou, J. Pela, M. Pesaresi, K. Petridis, M. Pioppi⁴⁹, D.M. Raymond, S. Rogerson, A. Rose, M.J. Ryan, C. Seez, P. Sharp[†], A. Sparrow, M. Stoye, A. Tapper, M. Vazquez Acosta, T. Virdee, S. Wakefield, N. Wardle, T. Whyntie

Brunel University, Uxbridge, United Kingdom

M. Chadwick, J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, D. Leggat, D. Leslie, W. Martin, I.D. Reid, P. Symonds, L. Teodorescu, M. Turner

Baylor University, Waco, U.S.A.

K. Hatakeyama, H. Liu, T. Scarborough

The University of Alabama, Tuscaloosa, U.S.A.

O. Charaf, C. Henderson, P. Rumerio

Boston University, Boston, U.S.A.

A. Avetisyan, T. Bose, C. Fantasia, A. Heister, J. St. John, P. Lawson, D. Lazic, J. Rohlf, D. Sperka, L. Sulak

Brown University, Providence, U.S.A.

J. Alimena, S. Bhattacharya, D. Cutts, Z. Demiragli, A. Ferapontov, U. Heintz, S. Jabeen, G. Kukartsev, E. Laird, G. Landsberg, M. Luk, M. Narain, D. Nguyen, M. Segala, T. Sinthuprasith, T. Speer, K.V. Tsang

University of California, Davis, Davis, U.S.A.

R. Breedon, G. Breto, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, R. Conway, P.T. Cox, J. Dolen, R. Erbacher, M. Gardner, R. Houtz, W. Ko, A. Kopecky, R. Lander, O. Mall, T. Miceli, D. Pellett, F. Ricci-Tam, B. Rutherford, M. Searle, J. Smith, M. Squires, M. Tripathi, R. Vasquez Sierra, R. Yohay

University of California, Los Angeles, Los Angeles, U.S.A.

V. Andreev, D. Cline, R. Cousins, J. Duris, S. Erhan, P. Everaerts, C. Farrell, J. Hauser, M. Ignatenko, C. Jarvis, C. Plager, G. Rakness, P. Schlein[†], P. Traczyk, V. Valuev, M. Weber

University of California, Riverside, Riverside, U.S.A.

J. Babb, R. Clare, M.E. Dinardo, J. Ellison, J.W. Gary, F. Giordano, G. Hanson, G.Y. Jeng⁵⁰, H. Liu, O.R. Long, A. Luthra, H. Nguyen, S. Paramesvaran, J. Sturdy, S. Sumowidagdo, R. Wilken, S. Wimpenny

University of California, San Diego, La Jolla, U.S.A.

W. Andrews, J.G. Branson, G.B. Cerati, S. Cittolin, D. Evans, F. Golf, A. Holzner, R. Kelley, M. Lebourgeois, J. Letts, I. Macneill, B. Mangano, S. Padhi, C. Palmer, G. Petrucciani, M. Pieri, M. Sani, V. Sharma, S. Simon, E. Sudano, M. Tadel, Y. Tu, A. Vartak, S. Wasserbaech⁵¹, F. Würthwein, A. Yagil, J. Yoo

University of California, Santa Barbara, Santa Barbara, U.S.A.

D. Barge, R. Bellan, C. Campagnari, M. D'Alfonso, T. Danielson, K. Flowers, P. Geffert, J. Incandela, C. Justus, P. Kalavase, S.A. Koay, D. Kovalskyi, V. Krutelyov, S. Lowette, N. Mccoll, V. Pavlunin, F. Rebassoo, J. Ribnik, J. Richman, R. Rossin, D. Stuart, W. To, C. West

California Institute of Technology, Pasadena, U.S.A.

A. Apresyan, A. Bornheim, Y. Chen, E. Di Marco, J. Duarte, M. Gataullin, Y. Ma, A. Mott, H.B. Newman, C. Rogan, M. Spiropulu, V. Timciuc, J. Veverka, R. Wilkinson, S. Xie, Y. Yang, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, U.S.A.

B. Akgun, V. Azzolini, A. Calamba, R. Carroll, T. Ferguson, Y. Iiyama, D.W. Jang, Y.F. Liu, M. Paulini, H. Vogel, I. Vorobiev

University of Colorado at Boulder, Boulder, U.S.A.

J.P. Cumalat, B.R. Drell, W.T. Ford, A. Gaz, E. Luiggi Lopez, J.G. Smith, K. Stenson, K.A. Ulmer, S.R. Wagner

Cornell University, Ithaca, U.S.A.

J. Alexander, A. Chatterjee, N. Eggert, L.K. Gibbons, B. Heltsley, A. Khukhunaishvili, B. Kreis, N. Mirman, G. Nicolas Kaufman, J.R. Patterson, A. Ryd, E. Salvati, W. Sun, W.D. Teo, J. Thom, J. Thompson, J. Tucker, J. Vaughan, Y. Weng, L. Winstrom, P. Wittich

Fairfield University, Fairfield, U.S.A.

D. Winn

Fermi National Accelerator Laboratory, Batavia, U.S.A.

S. Abdullin, M. Albrow, J. Anderson, L.A.T. Bauerick, A. Beretvas, J. Berryhill, P.C. Bhat, I. Bloch, K. Burkett, J.N. Butler, V. Chetluru, H.W.K. Cheung, F. Chlebana, V.D. Elvira, I. Fisk, J. Freeman, Y. Gao, D. Green, O. Gutsche, J. Hanlon, R.M. Harris, J. Hirschauer, B. Hooberman, S. Jindariani, M. Johnson, U. Joshi, B. Kilminster, B. Klima, S. Kunori, S. Kwan, C. Leonidopoulos, J. Linacre, D. Lincoln, R. Lipton, J. Lykken, K. Maeshima, J.M. Marraffino, S. Maruyama, D. Mason, P. McBride, K. Mishra, S. Mrenna, Y. Musienko⁵², C. Newman-Holmes, V. O'Dell, O. Prokofyev, E. Sexton-Kennedy, S. Sharma, W.J. Spalding, L. Spiegel, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, R. Vidal, J. Whitmore, W. Wu, F. Yang, F. Yumiceva, J.C. Yun

University of Florida, Gainesville, U.S.A.

D. Acosta, P. Avery, D. Bourilkov, M. Chen, T. Cheng, S. Das, M. De Gruttola, G.P. Di Giovanni, D. Dobur, A. Drozdetskiy, R.D. Field, M. Fisher, Y. Fu, I.K. Furic, J. Gartner, J. Hugon, B. Kim, J. Konigsberg, A. Korytov, A. Kropivnitskaya, T. Kypreos, J.F. Low, K. Matchev, P. Milenovic⁵³, G. Mitselmakher, L. Muniz, M. Park, R. Remington, A. Rinkevicius, P. Sellers, N. Skhirtladze, M. Snowball, J. Yelton, M. Zakaria

Florida International University, Miami, U.S.A.

V. Gaultney, S. Hewamanage, L.M. Lebolo, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida State University, Tallahassee, U.S.A.

T. Adams, A. Askew, J. Bochenek, J. Chen, B. Diamond, S.V. Gleyzer, J. Haas, S. Hagopian, V. Hagopian, M. Jenkins, K.F. Johnson, H. Prosper, V. Veeraraghavan, M. Weinberg

Florida Institute of Technology, Melbourne, U.S.A.

M.M. Baarmand, B. Dorney, M. Hohlmann, H. Kalakhety, I. Vodopiyanov

University of Illinois at Chicago (UIC), Chicago, U.S.A.

M.R. Adams, I.M. Anghel, L. Apanasevich, Y. Bai, V.E. Bazterra, R.R. Betts, I. Bucinskaite, J. Callner, R. Cavanaugh, O. Evdokimov, L. Gauthier, C.E. Gerber, D.J. Hofman, S. Khalatyan, F. Lacroix, M. Malek, C. O'Brien, C. Silkworth, D. Strom, P. Turner, N. Varelas

The University of Iowa, Iowa City, U.S.A.

U. Akgun, E.A. Albayrak, B. Bilki⁵⁴, W. Clarida, F. Duru, J.-P. Merlo, H. Mermerkaya⁵⁵,
A. Mestvirishvili, A. Moeller, J. Nachtman, C.R. Newsom, E. Norbeck, Y. Onel, F. Ozok⁵⁶,
S. Sen, P. Tan, E. Tiras, J. Wetzel, T. Yetkin, K. Yi

Johns Hopkins University, Baltimore, U.S.A.

B.A. Barnett, B. Blumenfeld, S. Bolognesi, D. Fehling, G. Giurgiu, A.V. Gritsan, Z.J. Guo,
G. Hu, P. Maksimovic, S. Rappoccio, M. Swartz, A. Whitbeck

The University of Kansas, Lawrence, U.S.A.

P. Baringer, A. Bean, G. Benelli, R.P. Kenny Iii, M. Murray, D. Noonan, S. Sanders,
R. Stringer, G. Tinti, J.S. Wood, V. Zhukova

Kansas State University, Manhattan, U.S.A.

A.F. Barfuss, T. Bolton, I. Chakaberia, A. Ivanov, S. Khalil, M. Makouski, Y. Maravin,
S. Shrestha, I. Svintradze

Lawrence Livermore National Laboratory, Livermore, U.S.A.

J. Gronberg, D. Lange, D. Wright

University of Maryland, College Park, U.S.A.

A. Baden, M. Boutemur, B. Calvert, S.C. Eno, J.A. Gomez, N.J. Hadley, R.G. Kellogg,
M. Kirn, T. Kolberg, Y. Lu, M. Marionneau, A.C. Mignerey, K. Pedro, A. Peterman,
A. Skuja, J. Temple, M.B. Tonjes, S.C. Tonwar, E. Twedt

Massachusetts Institute of Technology, Cambridge, U.S.A.

A. Apyan, G. Bauer, J. Bendavid, W. Busza, E. Butz, I.A. Cali, M. Chan, V. Dutta,
G. Gomez Ceballos, M. Goncharov, K.A. Hahn, Y. Kim, M. Klute, K. Krajczar⁵⁷,
P.D. Luckey, T. Ma, S. Nahn, C. Paus, D. Ralph, C. Roland, G. Roland, M. Rudolph,
G.S.F. Stephans, F. Stöckli, K. Sumorok, K. Sung, D. Velicanu, E.A. Wenger, R. Wolf,
B. Wyslouch, M. Yang, Y. Yilmaz, A.S. Yoon, M. Zanetti

University of Minnesota, Minneapolis, U.S.A.

S.I. Cooper, B. Dahmes, A. De Benedetti, G. Franzoni, A. Gude, S.C. Kao, K. Klapoetke,
Y. Kubota, J. Mans, N. Pastika, R. Rusack, M. Sasseville, A. Singovsky, N. Tambe,
J. Turkewitz

University of Mississippi, Oxford, U.S.A.

L.M. Cremaldi, R. Kroeger, L. Perera, R. Rahmat, D.A. Sanders

University of Nebraska-Lincoln, Lincoln, U.S.A.

E. Avdeeva, K. Bloom, S. Bose, J. Butt, D.R. Claes, A. Dominguez, M. Eads, J. Keller,
I. Kravchenko, J. Lazo-Flores, H. Malbouisson, S. Malik, G.R. Snow

State University of New York at Buffalo, Buffalo, U.S.A.

A. Godshalk, I. Iashvili, S. Jain, A. Kharchilava, A. Kumar

Northeastern University, Boston, U.S.A.

G. Alverson, E. Barberis, D. Baumgartel, M. Chasco, J. Haley, D. Nash, D. Trocino, D. Wood, J. Zhang

Northwestern University, Evanston, U.S.A.

A. Anastassov, A. Kubik, N. Mucia, N. Odell, R.A. Ofierzynski, B. Pollack, A. Pozdnyakov, M. Schmitt, S. Stoynev, M. Velasco, S. Won

University of Notre Dame, Notre Dame, U.S.A.

L. Antonelli, D. Berry, A. Brinkerhoff, K.M. Chan, M. Hildreth, C. Jessop, D.J. Karmgard, J. Kolb, K. Lannon, W. Luo, S. Lynch, N. Marinelli, D.M. Morse, T. Pearson, M. Planer, R. Ruchti, J. Slaunwhite, N. Valls, M. Wayne, M. Wolf

The Ohio State University, Columbus, U.S.A.

B. Bylsma, L.S. Durkin, C. Hill, R. Hughes, K. Kotov, T.Y. Ling, D. Puigh, M. Rodenburg, C. Vuosalo, G. Williams, B.L. Winer

Princeton University, Princeton, U.S.A.

N. Adam, E. Berry, P. Elmer, D. Gerbaudo, V. Halyo, P. Hebda, J. Hegeman, A. Hunt, P. Jindal, D. Lopes Pegna, P. Lujan, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, P. Piroué, X. Quan, A. Raval, B. Safdi, H. Saka, D. Stickland, C. Tully, J.S. Werner, A. Zuranski

University of Puerto Rico, Mayaguez, U.S.A.

E. Brownson, A. Lopez, H. Mendez, J.E. Ramirez Vargas

Purdue University, West Lafayette, U.S.A.

E. Alagoz, V.E. Barnes, D. Benedetti, G. Bolla, D. Bortoletto, M. De Mattia, A. Everett, Z. Hu, M. Jones, O. Koybasi, M. Kress, A.T. Laasanen, N. Leonardo, V. Maroussov, P. Merkel, D.H. Miller, N. Neumeister, I. Shipsey, D. Silvers, A. Svyatkovskiy, M. Vidal Marono, H.D. Yoo, J. Zablocki, Y. Zheng

Purdue University Calumet, Hammond, U.S.A.

S. Guragain, N. Parashar

Rice University, Houston, U.S.A.

A. Adair, C. Boulahouache, K.M. Ecklund, F.J.M. Geurts, W. Li, B.P. Padley, R. Redjimi, J. Roberts, J. Zabel

University of Rochester, Rochester, U.S.A.

B. Betchart, A. Bodek, Y.S. Chung, R. Covarelli, P. de Barbaro, R. Demina, Y. Eshaq, T. Ferbel, A. Garcia-Bellido, P. Goldenzweig, J. Han, A. Harel, D.C. Miner, D. Vishnevskiy, M. Zielinski

The Rockefeller University, New York, U.S.A.

A. Bhatti, R. Ciesielski, L. Demortier, K. Goulianos, G. Lungu, S. Malik, C. Mesropian

Rutgers, the State University of New Jersey, Piscataway, U.S.A.

S. Arora, A. Barker, J.P. Chou, C. Contreras-Campana, E. Contreras-Campana, D. Dugan, D. Ferencek, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, A. Lath, S. Panwalkar, M. Park, R. Patel, V. Rekovic, J. Robles, K. Rose, S. Salur, S. Schnetzer, C. Seitz, S. Somalwar, R. Stone, S. Thomas

University of Tennessee, Knoxville, U.S.A.

G. Cerizza, M. Hollingsworth, S. Spanier, Z.C. Yang, A. York

Texas A&M University, College Station, U.S.A.

R. Eusebi, W. Flanagan, J. Gilmore, T. Kamon⁵⁸, V. Khotilovich, R. Montalvo, I. Osipenkov, Y. Pakhotin, A. Perloff, J. Roe, A. Safonov, T. Sakuma, S. Sengupta, I. Suarez, A. Tatarinov, D. Toback

Texas Tech University, Lubbock, U.S.A.

N. Akchurin, J. Damgov, C. Dragoiu, P.R. Duderø, C. Jeong, K. Kovitanggoon, S.W. Lee, T. Libeiro, Y. Roh, I. Volobouev

Vanderbilt University, Nashville, U.S.A.

E. Appelt, A.G. Delannoy, C. Florez, S. Greene, A. Gurrola, W. Johns, P. Kurt, C. Maguire, A. Melo, M. Sharma, P. Sheldon, B. Snook, S. Tuo, J. Velkovska

University of Virginia, Charlottesville, U.S.A.

M.W. Arenton, M. Balazs, S. Boutle, B. Cox, B. Francis, J. Goodell, R. Hirosky, A. Ledovskoy, C. Lin, C. Neu, J. Wood

Wayne State University, Detroit, U.S.A.

S. Gollapinni, R. Harr, P.E. Karchin, C. Kottachchi Kankanamge Don, P. Lamichhane, A. Sakharov

University of Wisconsin, Madison, U.S.A.

M. Anderson, D. Belknap, L. Borrello, D. Carlsmith, M. Cepeda, S. Dasu, E. Friis, L. Gray, K.S. Grogg, M. Grothe, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbers, J. Klukas, A. Lanaro, C. Lazaridis, J. Leonard, R. Loveless, A. Mohapatra, I. Ojalvo, F. Palmonari, G.A. Pierro, I. Ross, A. Savin, W.H. Smith, J. Swanson

†: Deceased

1: Also at Vienna University of Technology, Vienna, Austria

2: Also at National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

3: Also at Universidade Federal do ABC, Santo Andre, Brazil

4: Also at California Institute of Technology, Pasadena, U.S.A.

5: Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland

6: Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France

7: Also at Suez Canal University, Suez, Egypt

8: Also at Zewail City of Science and Technology, Zewail, Egypt

9: Also at Cairo University, Cairo, Egypt

10: Also at Fayoum University, El-Fayoum, Egypt

11: Also at British University in Egypt, Cairo, Egypt

12: Now at Ain Shams University, Cairo, Egypt

- 13: Also at National Centre for Nuclear Research, Swierk, Poland
- 14: Also at Université de Haute-Alsace, Mulhouse, France
- 15: Now at Joint Institute for Nuclear Research, Dubna, Russia
- 16: Also at Moscow State University, Moscow, Russia
- 17: Also at Brandenburg University of Technology, Cottbus, Germany
- 18: Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
- 19: Also at Eötvös Loránd University, Budapest, Hungary
- 20: Also at Tata Institute of Fundamental Research - HECR, Mumbai, India
- 21: Also at University of Visva-Bharati, Santiniketan, India
- 22: Also at Sharif University of Technology, Tehran, Iran
- 23: Also at Isfahan University of Technology, Isfahan, Iran
- 24: Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran
- 25: Also at Facoltà Ingegneria, Università di Roma, Roma, Italy
- 26: Also at Università della Basilicata, Potenza, Italy
- 27: Also at Università degli Studi Guglielmo Marconi, Roma, Italy
- 28: Also at Università degli Studi di Siena, Siena, Italy
- 29: Also at University of Bucharest, Faculty of Physics, Bucuresti-Magurele, Romania
- 30: Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia
- 31: Also at University of California, Los Angeles, Los Angeles, U.S.A.
- 32: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
- 33: Also at INFN Sezione di Roma; Università di Roma, Roma, Italy
- 34: Also at University of Athens, Athens, Greece
- 35: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
- 36: Also at The University of Kansas, Lawrence, U.S.A.
- 37: Also at Paul Scherrer Institut, Villigen, Switzerland
- 38: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
- 39: Also at Gaziosmanpasa University, Tokat, Turkey
- 40: Also at Adiyaman University, Adiyaman, Turkey
- 41: Also at Izmir Institute of Technology, Izmir, Turkey
- 42: Also at The University of Iowa, Iowa City, U.S.A.
- 43: Also at Mersin University, Mersin, Turkey
- 44: Also at Ozyegin University, Istanbul, Turkey
- 45: Also at Kafkas University, Kars, Turkey
- 46: Also at Suleyman Demirel University, Isparta, Turkey
- 47: Also at Ege University, Izmir, Turkey
- 48: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
- 49: Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy
- 50: Also at University of Sydney, Sydney, Australia
- 51: Also at Utah Valley University, Orem, U.S.A.
- 52: Also at Institute for Nuclear Research, Moscow, Russia
- 53: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
- 54: Also at Argonne National Laboratory, Argonne, U.S.A.
- 55: Also at Erzincan University, Erzincan, Turkey
- 56: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
- 57: Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
- 58: Also at Kyungpook National University, Daegu, Korea